MCR-75-4
NAS8-30690

Interim
Report

February 1975

Experimental Study Of Transient Liquid Motion In Orbiting Spacecraft

(NASA-CR-144003) EXPERIMENTAL STUDY OF TRANSIENT LIQUID MOTION IN ORBITING SPACECRAFT Interim Report, Mar. 1974 - Feb. 1975 (Martin Marietta Corp.) 89 p HC $5.00
CSCL 22B G3/18

N76-11222

Unclas
03936

MARTIN MARIETTA

NAS8-30690 Interim Report February 1975

EXPERIMENTAL STUDY OF TRANSIENT LIQUID MOTION

Authors:

Robert L. Berry
James R. Tegart

MCR-75-4

Approved by:

George Morosow
Program Manager

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

FOREWORD

This report, prepared by the Martin Marietta Corporation, Denver Division, under Contract NAS8-30690, presents the results of an analytical and experimental study of transient liquid motion similar to that encountered in orbiting spacecraft. The study was performed from March 1974 to February 1975 and was administered by the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Huntsville, Alabama, under the direction of Mr. Frank Bugg.

ABSTRACT

This report presents the results of a twofold study of transient liquid motion such as that which will be experienced during orbital maneuvers by Space Tug. A test program was conducted in the Martin Marietta Low-g Test Facility involving twenty-two drops. Biaxial, low-g accelerations were applied to an instrumented, model propellant tank during free-fall testing, and forces exerted during liquid reorientation were measured and recorded. Photographic records of the liquid reorientation were also made. The test data was used to verify a mechanical analog which portrays the liquid as a point mass moving on an ellipsoidal constraint surface. The mechanical analog was coded into a Fortran IV digital computer program: LAMPS, Large AMPlitude Slosh. Test/analytical correlation indicates that the mechanical analog is capable of predicting the overall force trends measured during testing. More work is needed, however, to fine-tune the model through better understanding of viscous dissipative forces and improvements to liquid motion constraints.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to several individuals who contributed to the successful completion of this study. Mr. Frank Bugg, NASA MSFC, assisted in laying out the test program and monitored the entire study. Dr. Darrel Devers and Mr. Carl Bodley (Dynamics and Loads Section, Martin Marietta Corporation, Denver Division) made major contributions to the development of the mechanical analog. Dr. Devers authored Appendix A. Mr. Leonard Demchak, Dynamics and Loads, provided invaluable assistance in data reduction and computer program checkout. Mr. Dave Maytum and Mr. E. R. Wilson, Martin Marietta, Denver, made significant contributions to the design and construction of the test module. Mr. John Smith and Mr. Sam Reynolds fabricated the test module and performed the drop tower tests.

CONTENTS

LIST OF FIGURES

I. INTRODUCTION

In the immediate future, vehicles similar to Space Tug will perform orbital maneuvers while carrying a large mass of propellant. An in-depth understanding of the interaction forces between the propellant and space vehicle is required to properly assess the dynamics of these maneuvers, in particular, the docking maneuver. During orbital maneuvers, the propellant mass is subjected to small accelerations which can induce large amplitude slosh motion. Due to the relatively large mass of propellant, the forces exerted on the spacecraft by the moving propellant may have a significant effect on gross vehicle motion. Knowledge of these interaction forces is imparative in the design of vehicle orbital control systems and docking mechanisms.

A two-fold study has been conducted to develop a mechanical analog to simulate large amplitude liquid motion in a container for low-g environments. The primary purpose of the model is to simulate the interaction forces between liquids and the spacecraft due to moving propellant. The study consisted of both experimental and analytical tasks.

The Martin Marietta (Denver) Drop Test Facility was used in the conduct of the experimental phase. A test module capable of measuring large amplitude slosh forces on a scale model, axisymmetric tank was constructed. The test and liquid were scaled using dimensional analysis techniques to ensure simulation of motion representative of a full scale liquid oxygen tank. During testing, the module was dropped in the free-fall tower (simulating zero G) and small biaxial accelerations were applied. The ensuing liquid motion was photographed and two dimensional forces were measured and recorded. A total of twenty-two tests were conducted. Various tank fill volumes, tank orientations and acceleration magnitudes were investigated. The test time ($\approx$2 seconds) corresponds to approximately 15 seconds of liquid motion in a full size tank. Chapter II details the test program.

A mechanical analog was developed in the analytical phase to simulate the observed large amplitude slosh. The analog portrays the liquid as a point mass moving on a constraint surface which is represented by piecewise continuous elliptical segments. The constraint surface is the locus of liquid center of mass locations prescribed by slowly rotating the tank in a one-g field. The mechanical analog was implemented in a computer program, LAMPS (Large AMPlitude Slosh), which predicts force time histories on the tank due to the liquid motion. Chapter III presents a derivation of the equations of liquid motion and discusses the computer solution. A users guide to the program, LAMPS, is also presented.

In Chapter IV, a comparison between the acquired test data and computer predictions for the test configurations is presented.

II. EXPERIMENTAL INVESTIGATION

The primary objective of the experimental investigation was to generate data for correlation with the computer model developed under the analytical task. It was, therefore, required that the tests simulate the type of propellant motion that could occur during docking maneuvers of a spacecraft. In addition, it was necessary to measure the forces produced by the motion of the liquid. Scaling was used to relate the test conditions to a full-size tank. The drop tower, low-g test facility was selected as the means of performing the tests and a series of 22 drop tests was accomplished. Since the test conditions used have not been experimentally simulated before, the tests add to the basic understanding of the reorientation of propellant within a tank.

A. TEST MATRIX

The tests simulated the full-size liquid oxygen tank shown in Figure II-1. It has hemispherical end domes and a short cylindrical barrel section. The following test parameters were varied so that each test simulated a somewhat different condition under which the reorientation of the liquid occurs:

1. liquid volume;
2. inclination of the tank with respect to a vertical reference axis, given by the angle θX in Figure II-1;
3. magnitude of the acceleration acting on the tank: the acceleration is composed of two components, an axial acceleration and a lateral acceleration.

A lateral acceleration was applied in order to force the liquid to follow the tank wall. This avoids producing instabilities, in the form of a liquid column, that move through the center of the tank. Such instabilities have been shown to be a result of unique initial conditions and are not representative of a typical liquid reorientation. A further discussion of the occurrence of these instabilities can be found in Chapter IV.

The conditions for each test are listed in Table II-1. The acceleration specified is the axial acceleration for a full-size tank. In each case, a lateral acceleration with a magnitude of approximately ten percent of the axial acceleration was also applied.

Initially, the liquid was at rest, positioned as shown in Figure II-1. The gas/liquid interface was flat and perpendicular to the vertical reference axis. The specified acceleration was continuously applied and the liquid reoriented to the opposite end of the tank.

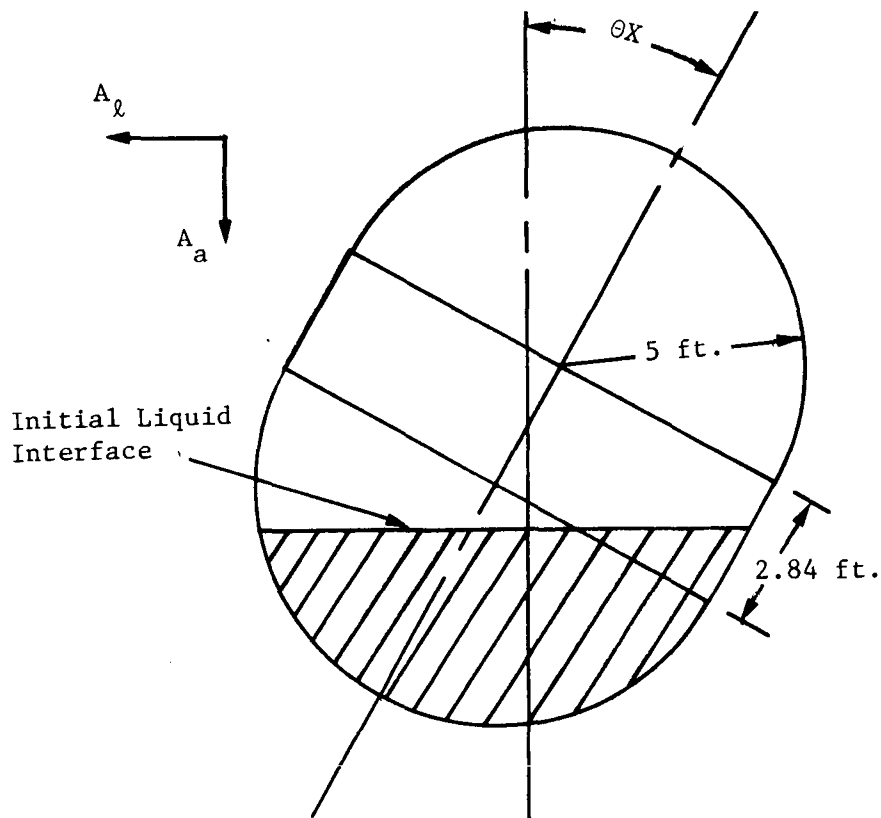


Figure II-1 Full-Size Tank

Table II-1. Test Matrix

Test Number	Liquid Volume (Percent)	Full-Size Tank Acceleration (g)	Tank Orientation Angle (Degrees)
1	25	.02	0
2	50	.02	0
3	75	.02	0
4	25	.02	30
5	50	.02	30
6	75	.02	30
7	25	.02	60
8	50	.02	60
9	75	.02	60
10	25	.02	90
11	50	.02	90
12	75	.02	90
13	25	.04	0
14	50	.04	0
15	75	.04	0
16	25	.04	45
17	50	.04	45
18	75	.04	45
19	25	.04	90
20	50	.04	90
21	75	.04	90
22	10	.04	0

B. TEST SCALING

The following variables characterize the reorientation of propellant within a tank:

ρ = liquid density,

μ = liquid viscosity,

σ = liquid surface tension,

θ = solid/liquid contact angle,

A = acceleration acting on liquid,

V = velocity of the gas-liquid interface,

v = liquid volume,

r = tank radius.

The force (F) and pressure (P) exerted by the liquid on the tank during liquid motion are the measured variables. Using the Buckingham pi theorem, the dimensionless parameters of interest can be established to be:

$$\pi_1 = F_r = \frac{V}{\sqrt{Ar}} \qquad \text{(Froude Number)}$$

$$\pi_2 = B_o = \frac{\rho A r^2}{\sigma} \qquad \text{(Bond Number)}$$

$$\pi_3 = R_e = \frac{\rho V r}{\mu} \qquad \text{(Reynolds Number)}$$

$$\left.\begin{aligned} \pi_4 &= \frac{F}{\rho A v} \\ \\ \pi_5 &= \frac{P}{\rho A r} \end{aligned}\right\} \text{Measured Variables}$$

With regard to the motion of the liquid, the Froude number can be related to the Bond number and Reynolds number as follows:

$$F_r = f\,(B_o, R_e)$$

Based on numerous propellant reorientation tests, numerical coefficients were established so that the above relationship can be expressed as follows (Reference 1):

$$F_r = K_{R_e} \left\{ 0.48 \left[1 - \left(\frac{0.84}{B_o} \right)^{\frac{B_o}{4.7}} \right] \right\}$$

Considering only the relationship between the Froude number and Bond number, their variation is shown graphically in Figure II-2. It can be seen that the Froude number is constant if the Bond number is greater than 10. This implies that surface tension forces are negligible, in comparison to the inertia and gravity forces, when B_o is greater than 10. The factor K_{R_e} in the equation accounts for viscous effects as a function of the Reynolds number. The variation of K_{R_e} is shown in Figure II-3. If the Reynolds number is greater than 50, viscous effects are negligible. Therefore, for any propellant reorientation which has a Bond number greater than 10 and a Reynolds number greater than 50, scaling can be based on Froude number alone.

As will be shown later, the above requirements for B_o and R_e are satisfied for the propellant reorientation conditions being considered here, so Froude number is the scaling parameter. That is

$$F_{r_a} = F_{r_m}$$

where the subscript "a" refers to the full-size system and the subscript "m" refers to the model. Therefore,

$$\frac{V_a}{\sqrt{A_a r_a}} = \frac{V_m}{\sqrt{A_m r_m}}$$

and $V \sim At$, where t = time. Hence,

$$\frac{t_a}{t_m} = \sqrt{\frac{A_m}{A_a} \frac{r_a}{r_m}}$$

The above equation yields the time scaling for a selected dimensional scaling and the ratio of the actual to model accelerations. It is independent of the liquid properties.

The liquid properties enter into the scaling in assuring that the Bond number and Reynolds number are sufficiently large. A large liquid density helps to make both R_e and B_o large, and also assures that the forces due to a given volume of liquid will be large. Low surface tension and viscosity are also desirable.

An evaluation of the various methods of producing the scaled test conditions showed that the drop tower test facility would best satisfy the above requirements. Martin Marietta's drop tower provides a specified low-g environment for a period of up to 2.1 seconds.

The values selected for A_m and r_m, in establishing the time scaling for the test, are somewhat constrained due to the drop tower test facility. In order to make the time scaling as large as possible (t_a large), A_m should be large. Large values of acceleration limit the test time in the drop tower because the drop capsule must be accelerated with respect to the drag shield; the travel distance is fixed. A value of 0.09g is a practical upper limit for A_m and will still provide 1.6 seconds of model test time.

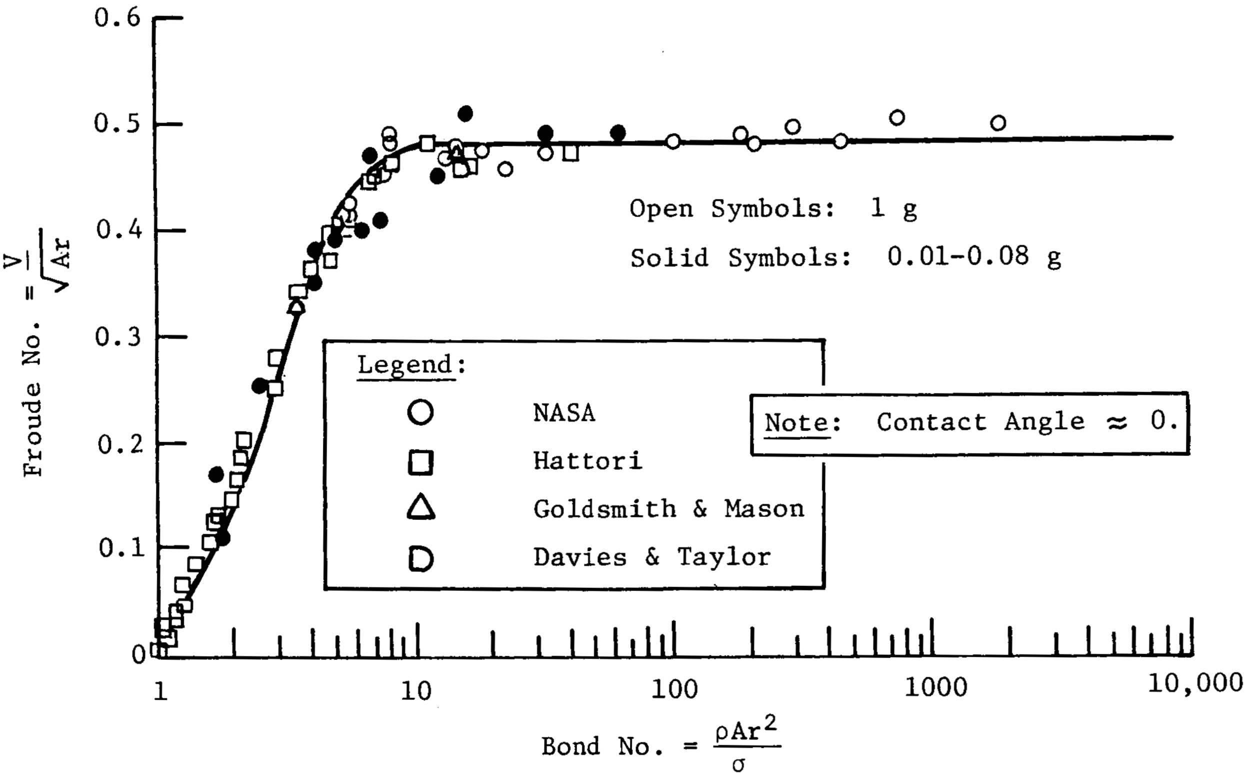


Figure II-2. Froude/Bond Number Relationship (from Reference 1)

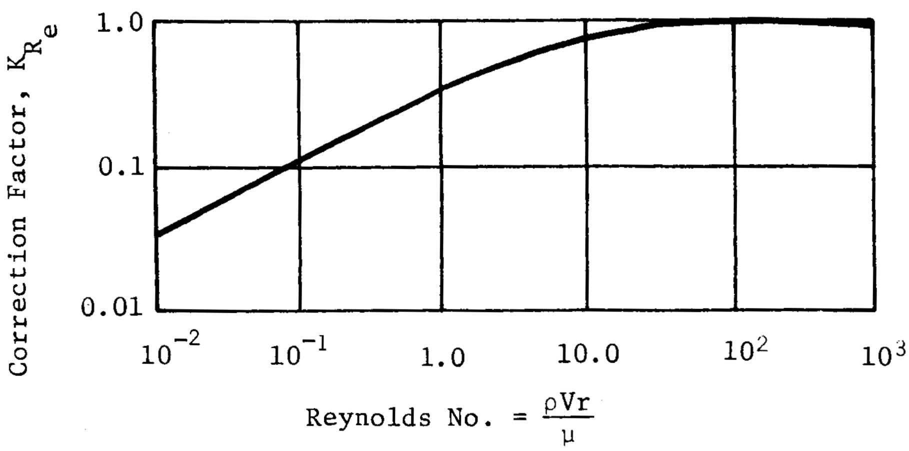


Figure II-3. Effect of Reynolds Number (from Reference 1)

In selecting r_m, it should be as small as possible in order to make t_a large. However, it must be realized that the forces produced by the liquid within the model are proportional to the mass of liquid. A value for r_m of 6.35 cm (2.5 inches) was selected as a suitable compromise between the two requirements. Therefore, the time scaling for r_a = 1.5 meters (5 feet) and A_a = 0.04g is

$$\frac{t_a}{t_m} = \sqrt{\frac{0.09}{0.04} \quad \frac{60}{2.5}} = 7.35$$

For a model test time of 1.6 seconds, the actual time simulated is 11.8 seconds. In simulating the case where A_a is 0.02g, the model acceleration is 0.045g and the ratio t_a/t_m remains the same. A model test period of 2.1 seconds was available at this lower acceleration, so t_a is equal to 15.4 seconds. The desired accelerations were achieved with spring motors producing 133N (30 lbf) and 66.7N (15 lbf) acting on a drop capsule weighing 162 Kg (358 lbm).

FC-43, a very dense fluorocarbon solvent, was selected as the test liquid. The properties of FC-43 (Reference 2) along with those of the actual liquid, oxygen, are listed in Table II-2.

TABLE II-2. LIQUID PROPERTIES

	FC-43 at 68^oF	Oxygen at 162^oR
Density, gm/cc (lbm/ft^3)	1.905(118.9)	1.14(71.3)
Surface Tension, dynes/cm (lbf/ft)	16.7(1.14x10^{-3})	13.5(9.25x10^{-4})
Viscosity, CP (lbm/ft-sec)	6.5(4.36x10^{-3})	0.195(1.31x10^{-4})
Contact Angle, degrees	0	0

The Bond number and Reynolds number for both the model and actual tank are listed in Table II-3. It can be seen that the requirements of the scaling analysis have been satisfied in both the actual case and the model. The Reynolds number is considerably greater than 50 in both cases, so viscous effects will be minimal. Both Bond numbers are greater than 10; however, there is a large difference between the Bond numbers of the full size tank and the model. When the Bond number is greater than 10, the effect of surface tension on the motion of the liquid is small. The minimum model Bond number of 208 should insure this to be true. The lateral acceleration acting on the model tank moves the liquid up one side of the tank, further reducing the effect of surface tension on the liquid motion. The large difference in Bond number between the full-size tank and the model indicates that the interface in the full-size tank would break up more than was observed in the model, but the general manner of the liquid motion will be the same.

TABLE II-3. BOND AND REYNOLDS NUMBERS

Parameter	Oxygen	FC-43
Bond Number		
$A_a = 0.02g$	3.85×10^4	208
$A_a = 0.04g$	7.70×10^4	407
Reynolds Number		
$A_a = 0.02g$	2.70×10^7	1.73×10^4
$A_a = 0.04g$	4.13×10^7	2.63×10^4

Since complete reorientation of the liquid during the test was desirable, this was also considered in selecting the model test conditions. It was anticipated that the liquid would be reoriented but some oscillation of the liquid about its equilibrium position would still be present at the end of the test.

Forces and pressures measured in the test may be scaled to the full-size tank, using the previously presented dimensionless parameters, as follows:

$$\frac{F_m}{F_a} = 2.71 \times 10^{-4}$$

and

$$\frac{P_m}{P_a} = 0.156$$

C. TEST SYSTEM DESCRIPTION

A test system that can produce the required subscale model test conditions and measure the liquid forces was designed and built for Martin Marietta's Drop Tower Test Facility. Flexibility to duplicate the varied test conditions, and sensitivity to record the small liquid forces, were the key requirements in designing the test system.

1. Test Module - The test module consists of the tank, force measuring links and slider mechanism. This module is shown mounted on the drop capsule in Figure II-4. Figures II-5 and II-6 present front and back views of the box in which the force links and tank are mounted.

The model tank is made of clear plastic. The domes were blown from sheet plastic and the barrel section was cut from a tube. The flange around the tank provides structural strength and permits the tank to be mounted at the proper angle within the force link yoke. Two screws in the barrel section of the tank allow it to be filled and drained.

Three force links, two vertical and one lateral, allow all forces acting on the tank to be measured. Bearings at each end of the links permit only forces along the link axis to be measured. The bearings that are mounted on the box are self-aligning.

Three flexures, perpendicular to the plane of the force links, prevent any motion of the tank out of that plane. The spring constant of these flexures is small in comparison to

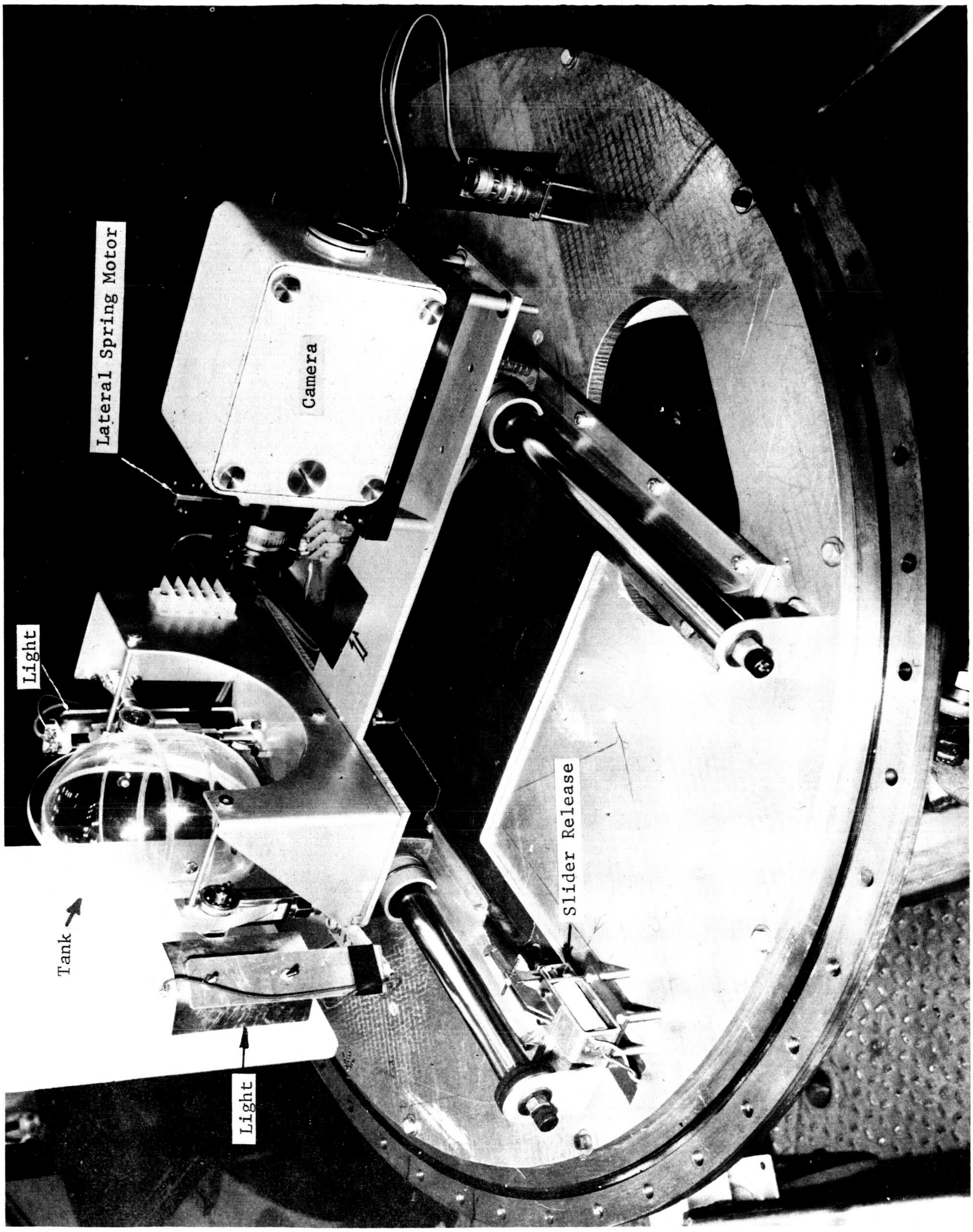


Figure II-4. Test Module Mounted on Drop Capsule

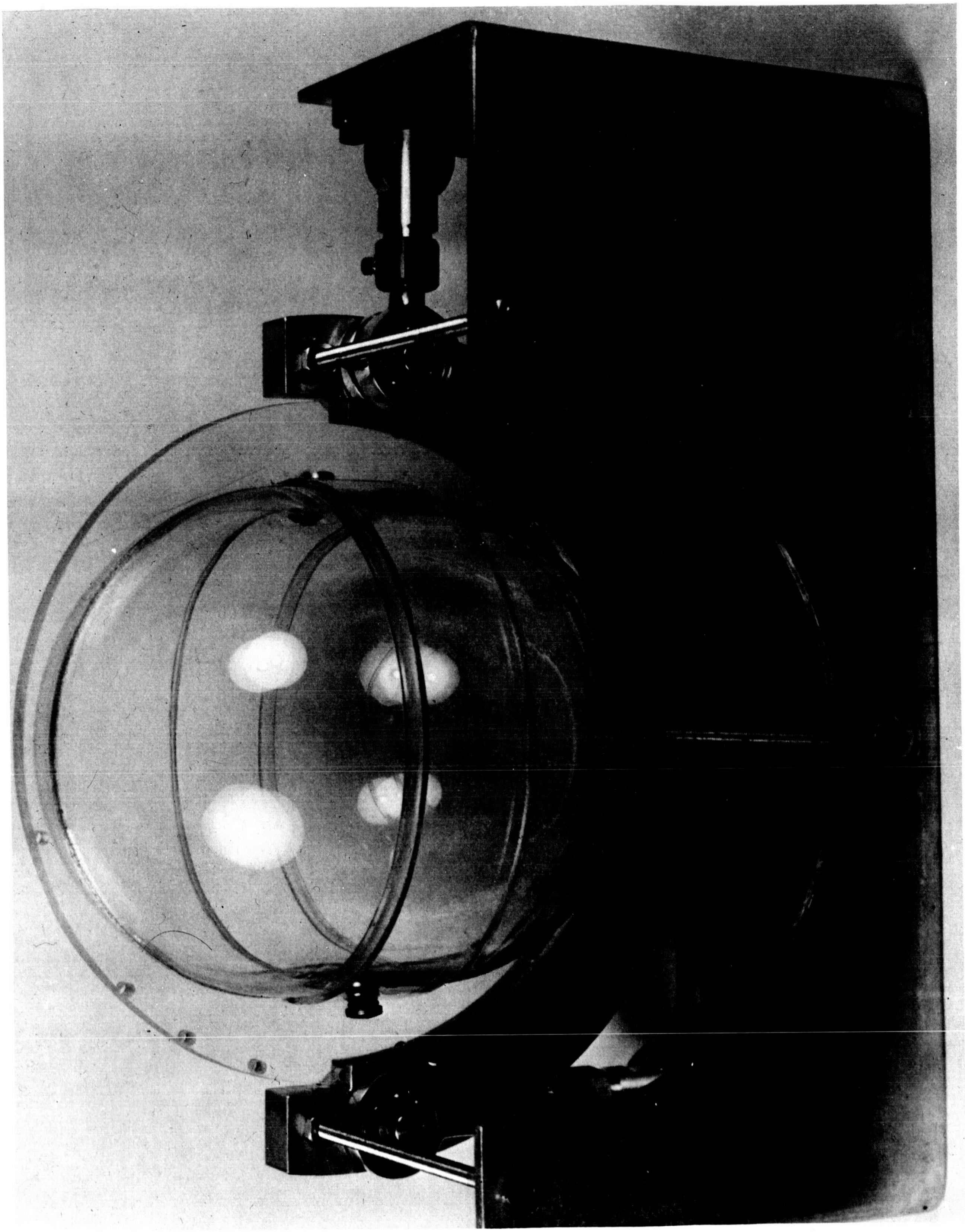


Figure II-5. Camera View of Tank and Force Links

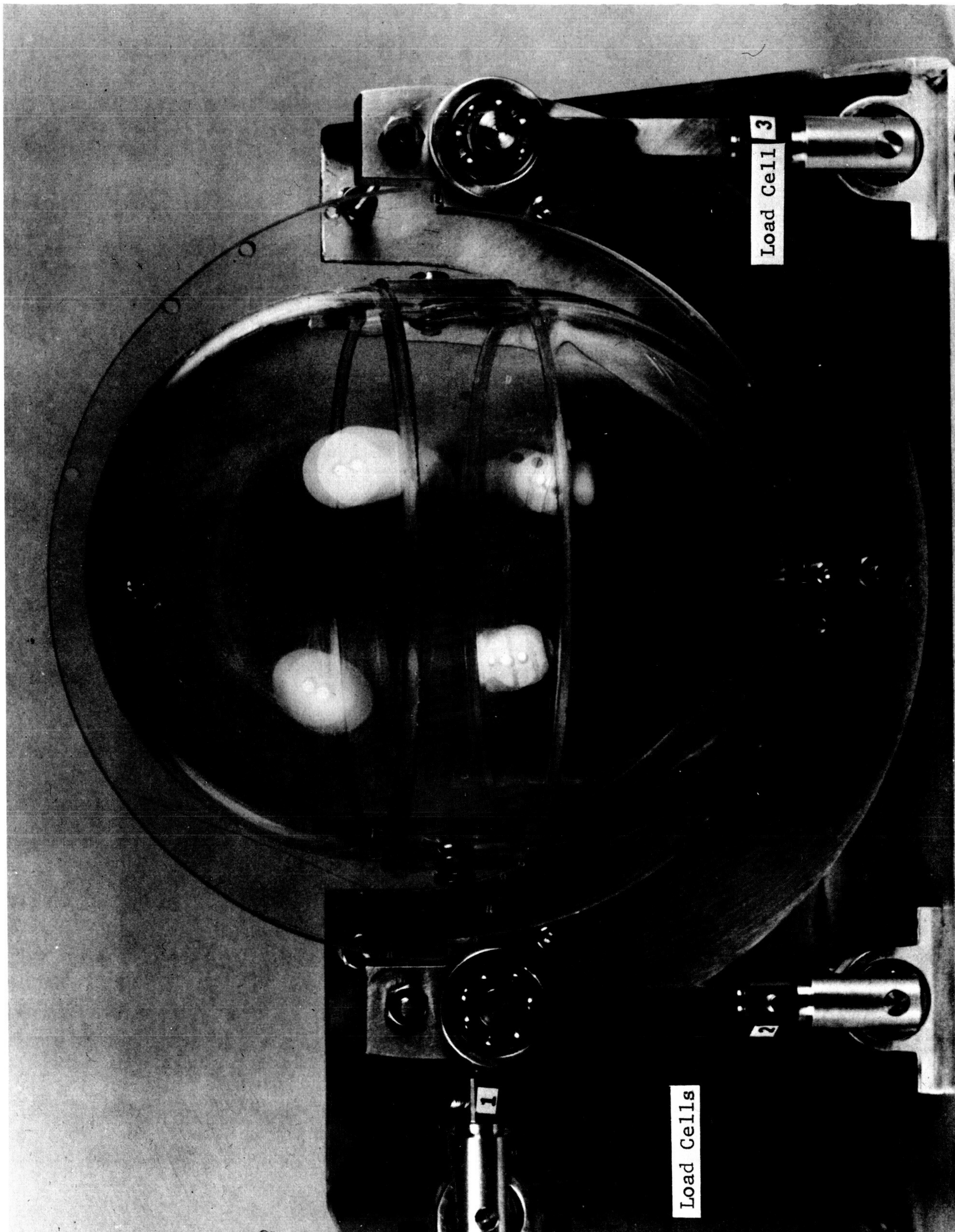


Figure II-6. Back View of Tank and Force Links the spring constant of the load cells and force links. Therefore, the effect of these flexures on the force sensed by the load cells is insignificant.

The platform of the slider is mounted to the rails with three linear bearings; one under the camera and two under the tank. A constant force spring motor provides the lateral acceleration of the slider. A spring motor with a force of 3.34N (0.75 lbf) accelerated the slider at approximately 0.02g. An electric solenoid was used to release the slider at the beginning of the test.

2. Drop Test Facility - The complete drop capsule is shown in Figure II-7. Due to the rather high accelerations being used, evacuation of the drag shield was not necessary. A simple frame was mounted over the test module rather than sealing the drop capsule with its cylindrical cover. The spring motors that provide the axial acceleration of the drop capsule and a crush tube are mounted on the conical base.

The total drop test system is illustrated in Figure II-8. The cable from the axial spring motor is extended and secured to the bottom of the drag shield. After releasing the drag shield from the top of the 23-meter (75-foot) drop tower, the drop capsule is simultaneously released within the drag shield. At the same time the solenoid is actuated releasing the slider. Both the lateral and axial spring motors accelerate the test module throughout the drop test. The drop capsule impacts the drag shield, with the crush tube absorbing the impact, and the drag shield lands in a bin of wheat at the end of the test.

3. Instrumentation - The motion of the liquid was recorded with a 16-mm Milliken DBM-3a camera mounted on the slider. The film speed was 200 frames per second. Immediately before the drag shield was released, the camera was started and it was automatically stopped when the drag shield impacted the wheat.

Quartz crystal load cells (Kistler Model 912) were used to measure the liquid forces. These load cells have a capacity of 2220N (500 lbf) in tension and 22200N (5000 lbf) in compression providing the capability of withstanding the impact at the end of the test. Peak, high frequency accelerations of up to 160g have been measured at impact. Due to their high degree of linearity, these load cells are fully capable of measuring the small forces due to the liquid motion.

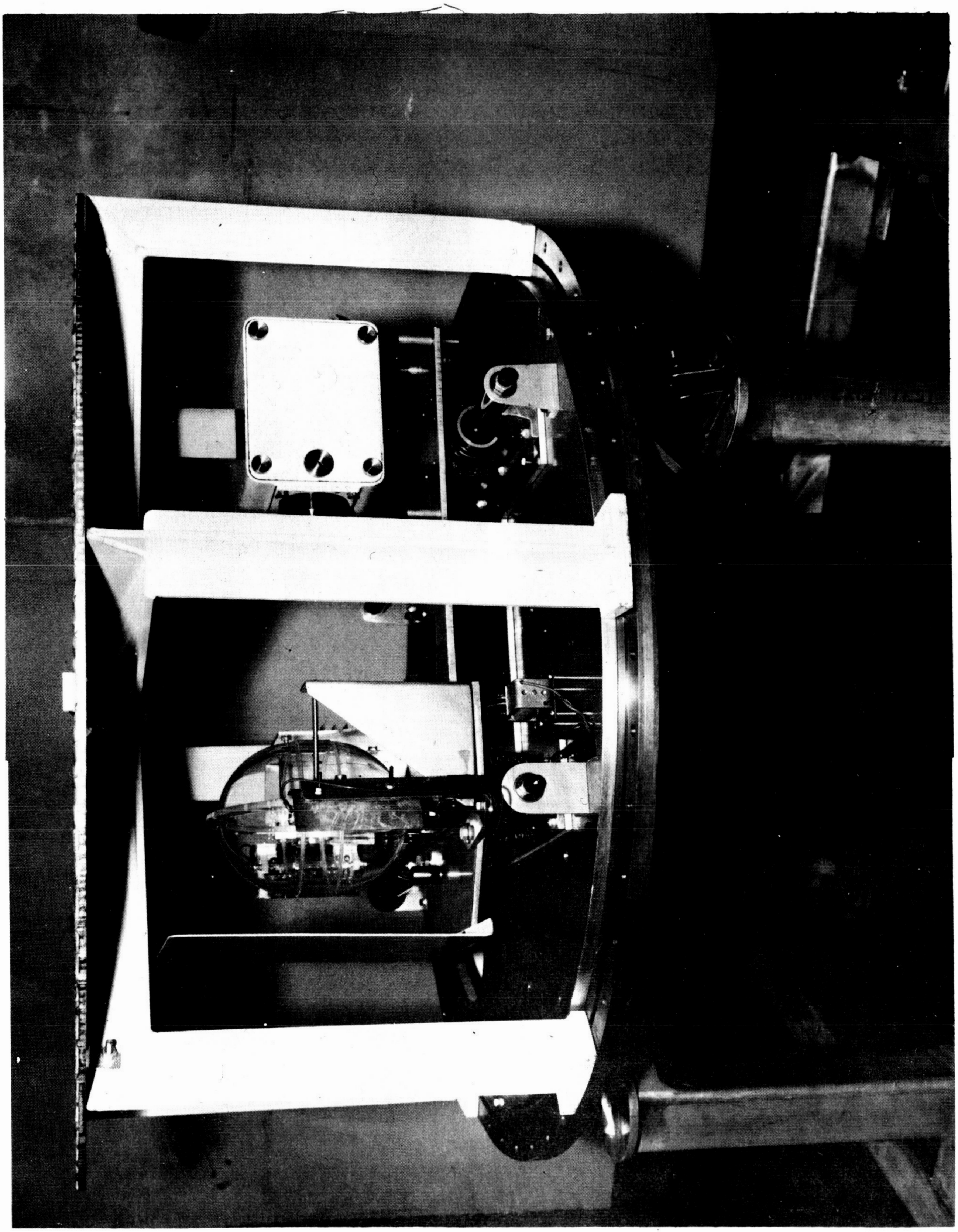


Figure II-7. Complete Drop Capsule

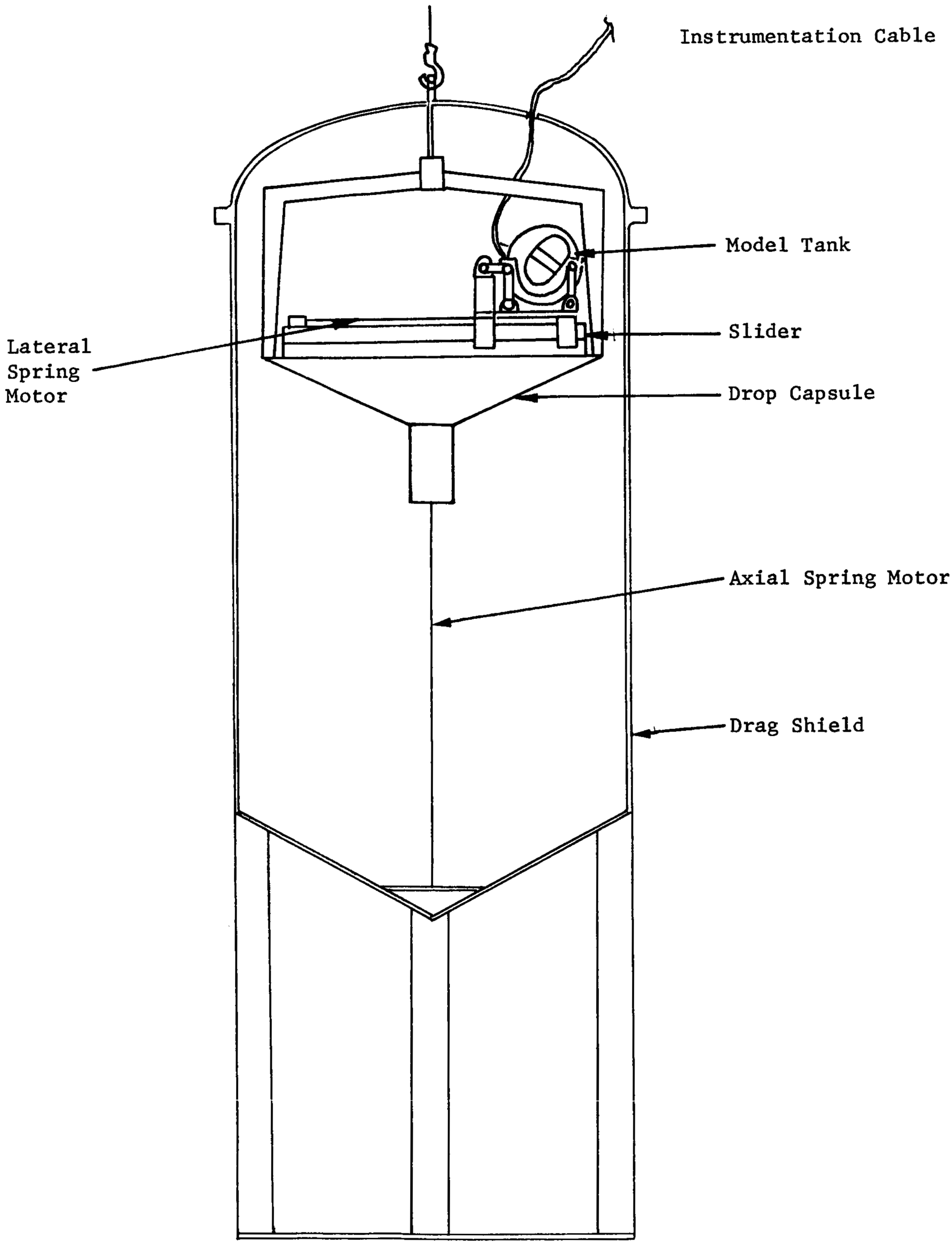


Figure II-8. Complete Drop Test System

The load cells were mounted in the force measuring links. Low noise cables were used to feed the output of the load cells to charge amplifiers. The charge amplifiers were located about half way up the drop tower to minimize the motion of the cable as the drag shield falls. The amplifiers were set on long time constant and the most sensitive scale that could be accommodated to measure the low amplitude and low frequency forces. Each charge amplifier input was momentarily grounded prior to the test, so all forces were measured with respect to zero at one-g.

The output of the charge amplifiers was fed in parallel to both a tape recorder and a chart recorder. In order to filter out the vibration induced by the camera motor, a 10 Hz low-pass filter was used in the amplifier for the chart recorder. An end-to-end calibration of the force measuring system was accomplished with the fixture shown in Figure II-9. Known weights were suspended from the hook at various positions with respect to the force links, the output was recorded on tape and then played back on the chart recorder.

An accelerometer (Columbia Model 302-2) was mounted on the slider to accurately measure the axial acceleration of the drop capsule. The accelerometer allowed the effect of drop capsule drag and piston effect due to its motion relative to the drag shield to be measured. It was found that these effects are negligible. The output of the accelerometer was handled in a manner similar to the load cells. A low noise cable fed the output to a charge amplifier and its output was recorded. The charge amplifier was grounded prior to the test so all accelerations were measured with respect to zero at one-g.

An attempt was made to measure the pressure of the liquid at various points on the tank during the reorientation. A Kulite miniature transducer was used with signal conditioning and amplification configured to measure pressures over a range of 0 to 0.07N/cm^2 (0.1 psi). The transducer could be mounted in any of three positions, so that it could always be located near the final equilibrium position of the reoriented liquid. Initially, the transducer was exposed to the ullage gas and it became submerged in liquid during the test. It was found that changes in output produced by the somewhat cooler liquid contacting the transducer was of the same order of magnitude expected for the pressure. No usable data was obtained from the pressure transducer.

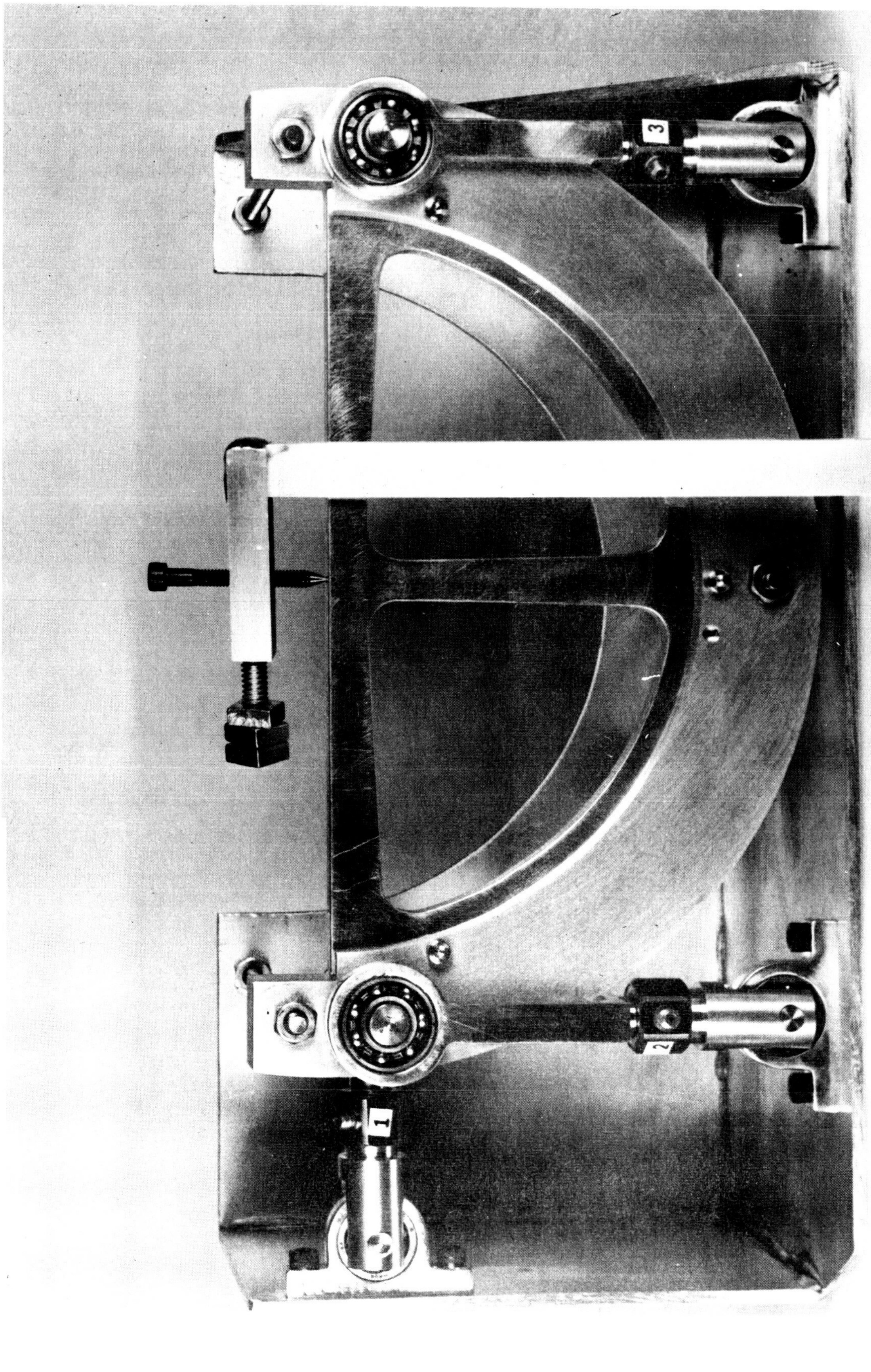


Figure II-9. Calibration Fixture

D. DATA REDUCTION

A lateral force (F_1) and two vertical forces (F_2 and F_3) were measured and recorded during the drop tests (see Figure II-6). The test data was manually scaled, and converted to a punch card data bank. The following steps were applied to each set of test data by a data reduction program. F_1, F_2 and F_3 were converted from voltages to forces by the appropriate scale factors. To smooth the data, somewhat, it was linearly interpolated with respect to time and a moving average digital low pass filter was applied to the data to remove 8 Hz to 12 Hz noise generated by the test support structure. Figure II-10 depicts the shape of the filter used. The force triad was then transposed into the tank triad as shown in Figure II-11. The following set of equations was used to perform the transposition,

$$FZ_I = F_2 + F_3$$

$$FY_I = F_1$$

$$MX_I = F_2 b + F_1 c - F_3 a$$

$$FZ_T = FZ_I \cos \theta X - FY_I \sin \theta X$$

$$FY_T = FY_I \cos \theta X + FZ_I \sin \theta X$$

$$MX_T = MX_I$$

where subscript (I) denotes the inertial triad and subscript (T) denotes the tank triad. The results were plotted with time as the ordinate.

To facilitate comparison between the test and analytical results, the test data was further adjusted. As previously mentioned, the force guages registered "0" in 1g prior to the drop. The analytical model records this one-g force as a negative force in the Z_I direction. To make the analysis and test results compatible, the initial zero test forces were converted to negative Z_I forces. This allows direct comparison between predicted and measured force time histories.

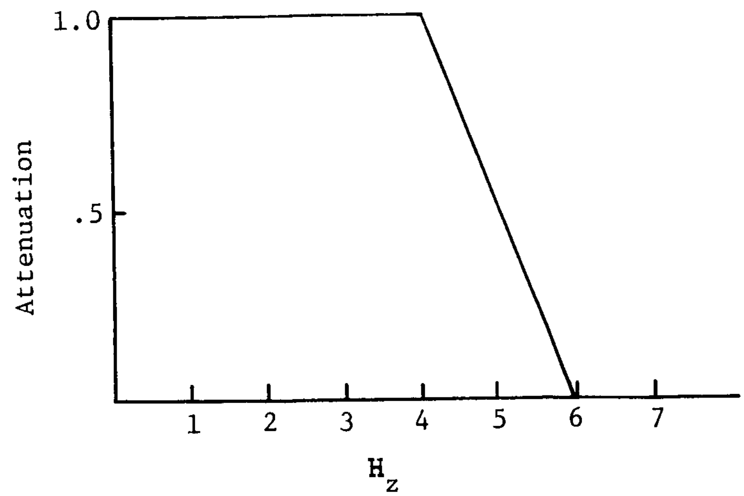


Figure II-10. Digital Filter Shape

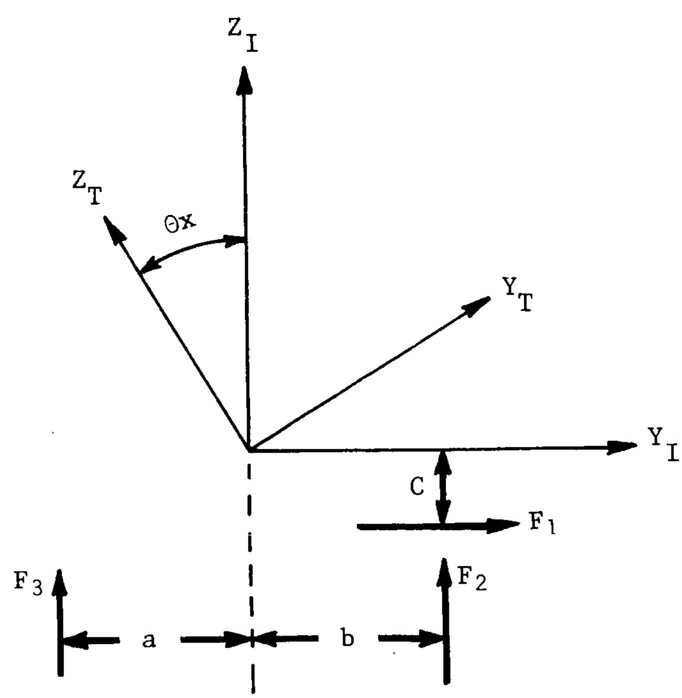


Figure II-11. Coordinate Systems

III. ANALYTICAL MODEL

A two dimensional mechanical analog has been developed to predict forces and moments exerted by a moving liquid on its container walls. In particular, the mechanical analog is designed to predict the forces exerted on an orbital spacecraft, such as the Space Tug, due to large amplitude propellant slosh initiated by small accelerations induced during docking or other orbital maneuvers. Knowledge of these forces is necessary in the design of spacecraft control systems and docking mechanisms.

The mechanical analog portrays the liquid as a point mass moving on a constraint surface. The constraint surface is determined by slowly rotating the tank (analytically) in a one-g field; the constraint surface is the locus of liquid center of mass (cm) locations prescribed during the rotation; assuming the free liquid surface is planar. This constraint surface is assumed to be axis-symmetric (with the tank body axis system); hence, one quadrant (90^o) is sufficient to describe the entire surface. In the mechanical analog, this constraint surface is approximated by piecewise continuous elliptical segments. When the liquid cm deviates substantially from the constraint surface, the coefficients of the ellipse are updated in order to bring the cm back to the constraint surface. For some tanks and fill volumes, it may be suitable to have a single ellipsoid to approximate the constraint surface while others may require several segments to appropriately describe it. Forces that the liquid exerts on the container result from inertial reactive forces and viscous dissipative forces.

A. EQUATIONS OF MOTION

The two dimensional equations of motion for the coupled tank/fluid system are stated in canonical first order form. This form of the equations of motion fall within a framework which will accommodate an entire spacecraft even though the following discussions are limited to simulation of the test configuration. The goal is to verify the mechanical analog based on test results. Appendix A addresses the extension of the equations of motion to the coupled spacecraft/tank/fluid system.

Figure III-1 depicts the relationship of the tank body and inertial coordinate systems used in the mechanical analog. The constraint surface and its elliptical approximation are also shown.

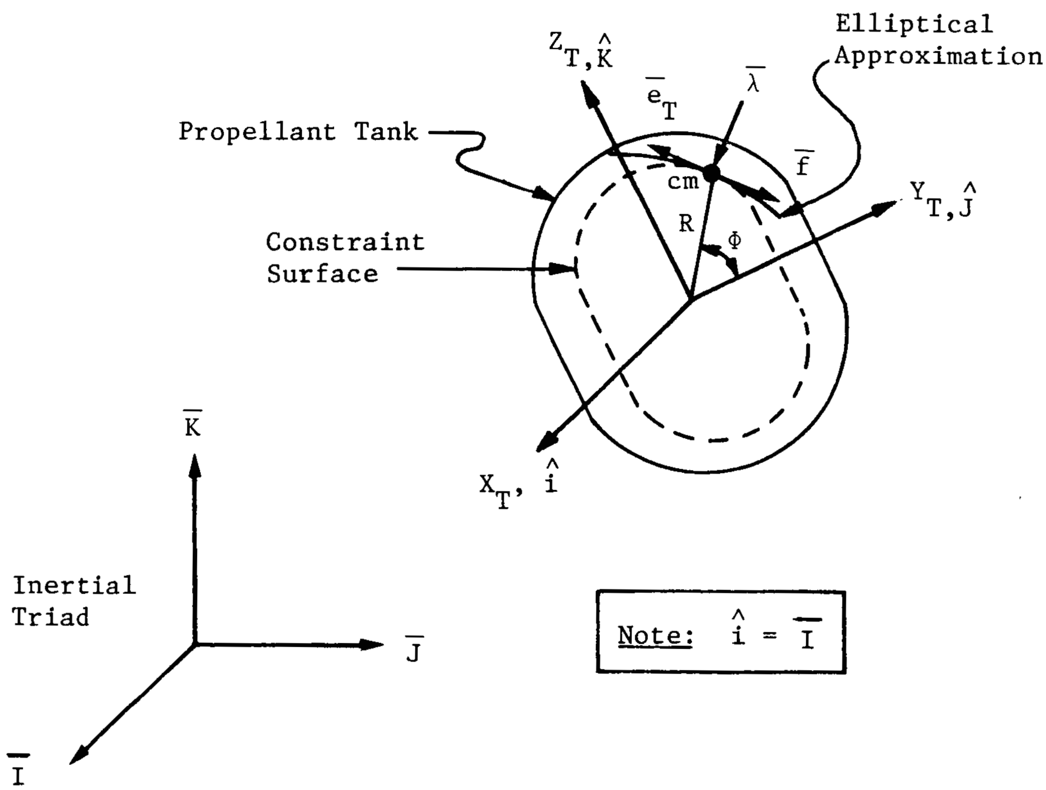


FIGURE III-1. COORDINATE SYSTEMS

The force balance on the fluid cm can be written as follows:

$$M_F \frac{d}{dt} (\bar{V}_F) = \bar{\lambda} + \bar{f} \tag{1}$$

where: M_F = fluid mass,

$\overline{V}_F$ = velocity vector of the fluid cm relative to the inertial frame,

$\overline{\lambda}$ = constraint force normal to the constraint surface (inertial reactive force),

$\overline{f}$ = viscous dissipative force on the fluid cm tangent to the constraint surface.

The fluid cm is constrained to move in the Y_T-Z_T plane on the constraint surface, approximated by elliptical segments. Hence, the fluids velocity vector must be instantaneously tangent to the approximated surface. This is equivalent to writing:

$$(\overline{V}_F - \overline{V}_a) \cdot \overline{\nabla} E = 0 \qquad (2)$$

where: $\overline{V}_a$ = velocity vector of the point on the constraint surface (coincident with the fluid cm) relative to the inertial frame,

$\overline{\nabla}E$ = planar gradient of the constraint surface (outward normal vector), $\frac{\partial E}{\partial Y} \hat{j} + \frac{\partial E}{\partial Z} \hat{k}$.

The velocity of the fluid cm may be defined as follows:

$$\overline{V}_F = \overline{V}_a + V_T \overline{e}_T \qquad (3)$$

where: V_T = magnitude of the fluid cm velocity relative to the constraint surface with the tank triad as a reference,

$\overline{e}_T$ = unit vector tangent to the constraint surface.

Differentiating equation (3) yields,

$$\dot{\overline{V}}_F = \overline{A}_a + \dot{V}_T \, \overline{e}_T + V_T \, \dot{\overline{e}}_T \tag{4}$$

where: $\overline{A}_a$ = the acceleration vector applied during the test resolved to the tank triad, $\overline{A}_a = A_j \hat{j} + A_k \hat{k}$

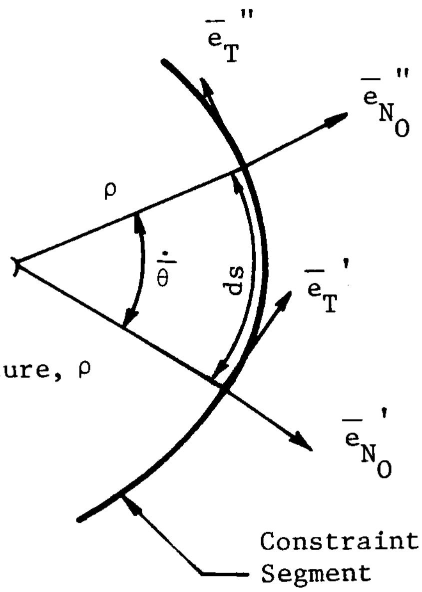


FIGURE III-2. DETERMINATION OF $\dot{\overline{e}}_T$

From kinematics and Figure III-2, we can develop an expression for $\dot{\overline{e}}_T$ as follows:

$$\dot{\overline{e}}_T = \dot{\overline{\theta}} \times \overline{e}_T \tag{5}$$

$$V_T = \frac{ds}{dt} \tag{6}$$

$$\frac{ds}{dt} = \rho \, \dot{\theta} \tag{7}$$

Since the fluid cm must move in the Y_T-Z_T plane, from equations (6) and (7), we can write

$$\dot{\bar{\theta}} = \frac{V_T}{\rho} (\bar{e}_{N_o} \times \bar{e}_T) \qquad (8)$$

where $\bar{e}_{N_o} \times \bar{e}_T$ determines the sign of $\dot{\bar{\theta}}$. Substituting equation (8) into equation (5) we have an expression for $\dot{\bar{e}}_T$,

$$\dot{\bar{e}}_T = \frac{V_T}{\rho} (\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T \qquad (9)$$

Now substituting equation (9) into (4), $\dot{\bar{V}}_F$ may be written,

$$\dot{\bar{V}}_F = \bar{A}_a + \dot{V}_T \bar{e}_T + \frac{V_T^2}{\rho} ((\bar{e}_{N_o} \times \bar{e}_T) \times e_T) \qquad (10)$$

Combining equations (10) and (1), we have the general equation of motion of the fluid cm represented in terms of the tank coordinate system,

$$\bar{A}_a + \dot{V}_T \bar{e}_T + \frac{V_T^2}{\rho} ((\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T) = \frac{1}{M_F} (\bar{\lambda} + \bar{f}) \qquad (11)$$

In order to solve for $\dot{V}_T$ we can convert to a scalar equation by performing a vector dot product on equation (11) with $\bar{e}_T$.

$$\bar{e}_T \cdot \left[\bar{A}_a + \dot{V}_T \bar{e}_T + \frac{V_T^2}{\rho} ((\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T)\right] = \frac{1}{M_F} (\bar{e}_T \cdot \bar{\lambda} + \bar{e}_T \cdot \bar{f}) \qquad (12)$$

Note: $\bar{e}_T \cdot \bar{\lambda} = 0$ .... since they are perpendicular,

$\bar{e}_T \cdot \bar{f} = -f$ ... since they are parallel and in opposite directions,

f = magnitude of the viscous dissipative force.

Solving for $\dot{V}_T$ from equation (12) yields

$$\dot{V}_T = \frac{-f}{M_F} - (\bar{e}_T \cdot \bar{A}_a) - \frac{V_T^2}{\rho}\left[\bar{e}_T \cdot ((\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T)\right] \quad (13)$$

Note: $(\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T = -\bar{e}_{N_o}$ .... unit inward normal vector to the constraint surface,

hence, $\bar{e}_T \cdot ((\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T) = \bar{e}_T \cdot (-\bar{e}_{N_o}) = 0$ .... they are perpendicular.

Equation (13) can now be rewritten as follows,

$$\dot{V}_T = \frac{-f}{M_F} - (\bar{e}_T \cdot \bar{A}_a) \quad (14)$$

If $\bar{e}_T$ is defined in terms of its components, g and h, in the tank triad, equation (14) can be written, $\{\bar{e}_T = g\,\hat{j} + h\,\hat{k}\}$

$$\dot{V}_T = \frac{-f}{M_F} - g\,A_j - h\,A_k \quad (15)$$

From equation (15) we note that $\dot{V}_T$ is a function of the components of the unit tangent vector, $\bar{e}_T$. Both of these components, g and h, must vary with time in order to keep $\bar{e}_T$ tangent to the constraint surface as the fluid cm moves through the tank.

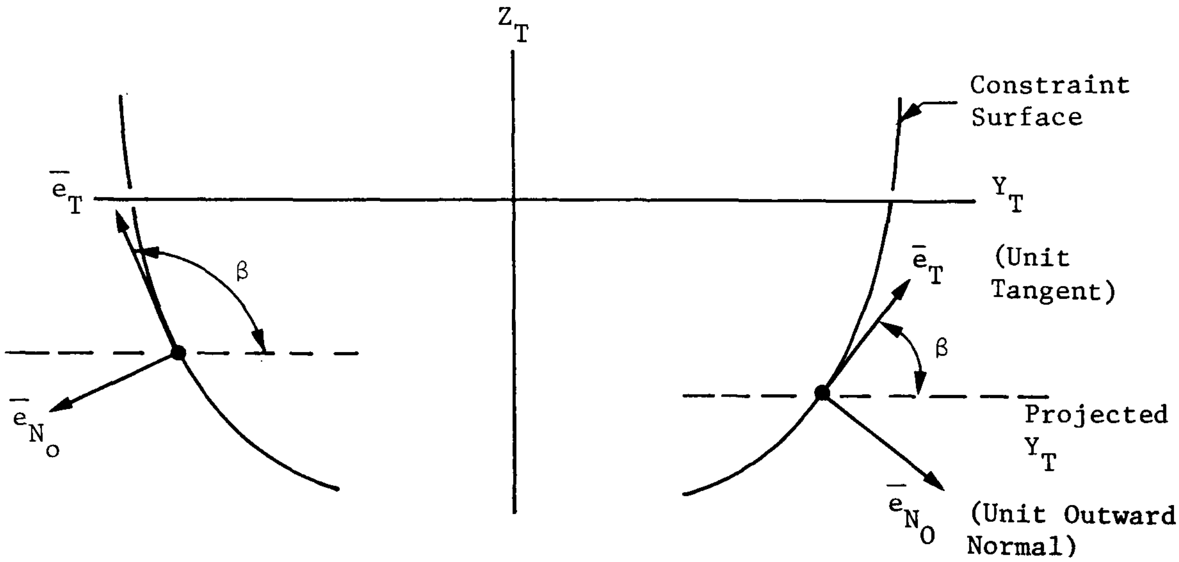


FIGURE III-3. ORIENTATION OF UNIT TANGENT AND OUTWARD NORMAL VECTORS TO THE CONSTRAINT SURFACE. DEFINITION OF β .

From Figure III-3, it can be seen that at any instant of time, $\bar{e}_T$ is at an angle β with respect to the Y_T axis. From Figure III-2, we note that $\beta = \theta + 90^\circ$, hence $\dot{\beta} = \dot{\theta}$. Therefore, from equations (6) and (7),

$$\dot{\beta} = \frac{V_T}{\rho} \tag{16}$$

From Figure III-3, we can also write,

$$g = \cos\beta$$
$$h = \sin\beta \tag{17}$$
$$\sqrt{g^2 + h^2} = 1$$

Equation (15) now can be written,

$$\dot{V}_T = \frac{-f}{M_F} - A_j \cos \beta - A_k \sin \beta \tag{18}$$

Equations (16) and (18) are the state equations for the fluid cm and are numerically integrated to yield the state variables V_T and β. The direction of the unit tangent vector, $\bar{e}_T$, must be initially determined in order to begin integration of equation (18) (i.e., β @ t=0). In the mechanical analog V_{T_o} is always assumed zero.

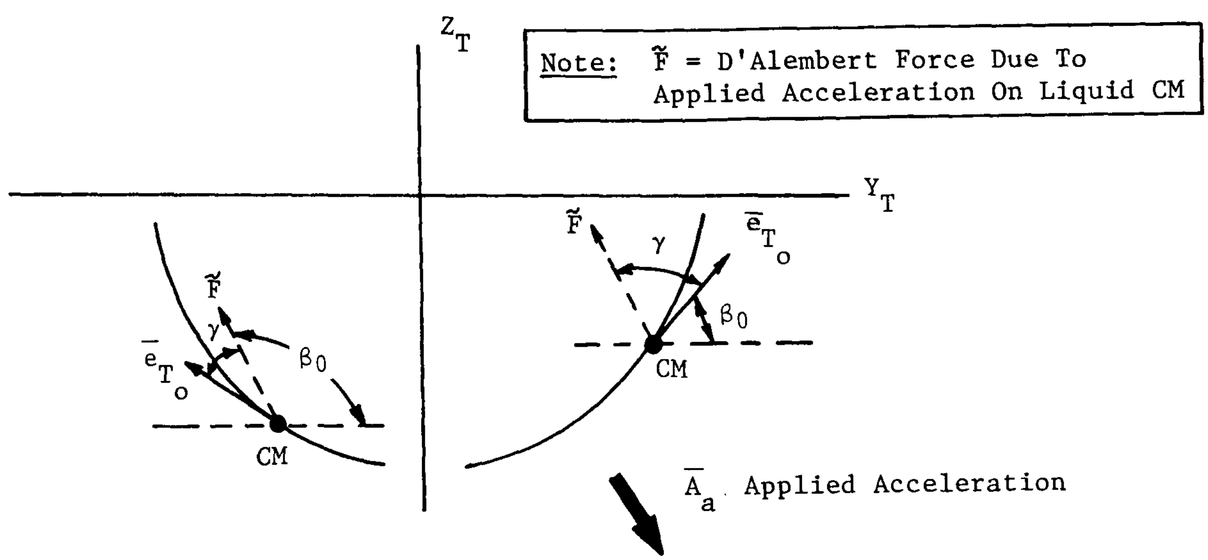


FIGURE III-4. INITIAL DIRECTION OF $\bar{e}_T$

Figure III-4 delineates, for two initial cm locations, the initial direction, β_o, of the unit tangent vector, $\bar{e}_T$. From kinematics we know that the velocity vector of the fluid cm must initially have a component in the direction of the D'Alembert force, $\tilde{F}$. This is equivalent to writing:

$$\bar{e}_T \cdot \tilde{F} = |\bar{e}_T| \, |\tilde{F}| \cos \gamma \geq 0 \tag{19}$$

The D'Alembert force, $\tilde{F}$, can be shown to have the same direction as the negative of the applied acceleration,

$$\frac{\tilde{F}}{|\tilde{F}|} = \frac{-\bar{A}_a}{|\bar{A}_a|} \tag{20}$$

The inequality in equation (19) can only be satisfied for $0^\circ \leq |\gamma| \leq 90^\circ$. In the mechanical analog, if $\gamma = 90^\circ$, the fluid will not move since it is required to move on the constraint surface. Determination of the value of β_0 requires some additional information which is provided by the following equation.

$$\bar{e}_T \cdot \bar{\nabla} E = 0 \tag{21}$$

Equation (21) states that the tangent vector must be perpendicular to the normal vector at the initial fluid cm location. The simultaneous solution to equations (19) and (21), recalling equation (17), provides the initial value of β.

1. Fluid Force Determination - The constraint force $\bar{\lambda}$ (inertial reactive) is determined by performing a vector dot product on equation (11) with the unit outward normal vector, $\bar{e}_{N_o}$. Where

$$\bar{e}_{N_o} = \frac{\bar{\nabla} E}{|\bar{\nabla} E|}$$

$$\bar{e}_{N_o} \cdot \bar{A}_a + \dot{V}_T (\bar{e}_{N_o} \cdot \bar{e}_T) + \frac{V_T^2}{\rho} (\bar{e}_{N_o} \cdot ((\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T)) = \frac{(\bar{e}_{N_o} \cdot \bar{\lambda})}{M_F} + \frac{(\bar{e}_{N_o} \cdot \bar{f})}{M_F} \tag{22}$$

Note: $\bar{e}_{N_o} \cdot \bar{e}_T = 0$ .... they are perpendicular,

$\bar{e}_{N_o} \cdot \bar{f} = 0$ .... they are perpendicular,

$\bar{e}_{N_o} \cdot ((\bar{e}_{N_o} \times \bar{e}_T) \times \bar{e}_T) = -1$ .... they are parallel and in opposite directions,

$\bar{e}_{N_o} \cdot \bar{\lambda} = -\lambda$ .... assuming that the inertial reactive force acts opposite the outward normal.

Hence, equation (22) reduces to:

$$(\bar{e}_{N_o} \cdot \bar{A}_a) - \frac{V_T^2}{\rho} = \frac{-\lambda}{M_F} \qquad (23)$$

or $$\lambda = M_F \left[\frac{V_T^2}{\rho} - (\bar{e}_{N_o} \cdot \bar{A}_a) \right] \qquad (24)$$

In equation (24) λ is assumed to act opposite the outward normal vector to the constraint surface. If, in fact, it should act in the same direction as the outward normal vector, λ will have a negative sign. For example, at t=0, when V_T=0, this condition occurs. This indicates a load relief on the propellant tank and represents the actual phenomena that occurs, provided the fluid is initially oriented due to some initial acceleration gradient and is not initially in zero-g.

The viscous dissipative force, $\bar{f}$, is a real unknown. Its characteristics are not well-defined, but previous investigations (Reference 3) indicate that significant parameters may be kinematic viscosity, characteristic length, and gravitational environment. The mechanical analog represents f as a function of velocity, V_T, and the inertial reactive force, λ .

$$f = \mu \left|\bar{\lambda}\right| + \eta \left|\bar{V}_T\right| \quad ; \quad \mu , \eta \geq 0 \qquad (25)$$

The parameters μ and η are variables input to the model. Their values may be approximated from test data or by consideration of the fluid properties and tank construction.

2. Additional Equations - The radius of curvature used in equation (16) can be determined from the elliptical surface equation.

$$E = aY^2 + cZ^2 - 1 = 0, \text{ Constraint Surface} \qquad (26)$$

Solving equation (26) for Y:

$$Y = \left[\frac{1 - cZ^2}{a}\right]^{\frac{1}{2}} \tag{27}$$

The radius of curvature is defined as,

$$\rho = \text{ABS}\left[\frac{\left[1 + \left(\frac{dY}{dZ}\right)^2\right]^{3/2}}{\frac{d^2Y}{dZ^2}}\right] \text{, evaluated at the cm location (y,z)} \tag{28}$$

Similarly, ρ can be defined as follows,

$$\rho = \text{ABS}\left[\frac{\left[1 + \left(\frac{dZ}{dY}\right)^2\right]^{3/2}}{\frac{d^2Z}{dY^2}}\right] \text{, evaluated at the cm location (y,z)} \tag{29}$$

In addition to the equations developed above, some other position variables are desirable for programming purposes. In particular, the fluid cm position (y,z) in the tank body system is needed. The initial location (@ t=0) is determined by a Newton Raphson iteration on fluid volume in subroutine FLUDCG, based on an initial acceleration field. Once integration of the equations of motion begins, the fluid cm location can be determined from the surface equation, equation (26), and the instantaneous tangent vector, $\bar{e}_T$. Recalling the definition of $\bar{e}_T$ and $\bar{\nabla} E$, we can write:

$$\bar{e}_T \cdot \bar{\nabla} E = 0 = aY \cos\beta + cZ \sin\beta \tag{30}$$

therefore, $$Y = -\frac{cZ}{a} \text{TAN } \beta \tag{31}$$

Combining equations (26) and (31), we can solve for Z.

$$Z = \left[\frac{1}{\left(\frac{c^2}{a}\ \mathrm{TAN}^2 \beta + c\right)}\right]^{\frac{1}{2}} \tag{32}$$

In equation (31), β is a state variable determined by integration while a and c are the ellipsoidal surface coefficients. From equation (27) we can define Y in terms of Z. Therefore, equations (27) and (32) define the magnitudes of Y and Z. Their signs are initially determined by subroutine FLUDCG and then determined by tracking fluid cm crossings of the Y_T and Z_T axes.

The polar location of the fluid cm can now easily be determined as follows (Figure III-1).

$$R = \left[Y^2 + Z^2\right]^{\frac{1}{2}} \tag{33}$$

$$\Phi = \mathrm{ARCTAN}\left(\frac{Z}{Y}\right) \tag{34}$$

The desired output of the mechanical analog is the time history of forces exerted on the tank and supports by the moving fluid. Equations (24) and (25), λ and f, define the forces acting on the fluid cm. These forces must be transformed to those acting on the tank for comparison with test. In Chapter II, the test configuration was identified. It should be noted that the force measurement system, load cells, measures not only the forces exerted by the moving fluid but also inertial forces due to the tank and support structure mass. To facilitate the comparison between test and analytical results, these inertial forces have been included in the mechanical analog. The forces and moment (in the tank body system) corresponding to those measured in the tests may be expressed as follows

$$FY = f \cos \beta + \lambda e N_{o_j} - A_j M_s \tag{35}$$

$$FZ = f \sin\beta + \lambda e_{N_{o_k}} - A_k M_s \tag{36}$$

$$MX = (f \sin\beta + \lambda e_{N_{o_k}}) Y - (f \cos\beta + \lambda e_{N_{o_j}}) Z \tag{37}$$

where: M_s = mass of tank and support structure,

$e_{N_{o_j}}$, $e_{N_{o_k}}$ = components of the unit outward normal vector,

$$\overline{e}_{N_o} = e_{N_{o_j}} \hat{j} + e_{N_{o_k}} \hat{k}$$

3. Summary of Equations to be Solved

State equations: $$\dot{V}_T = \frac{-f}{M_F} - A_j \cos\beta - A_k \sin\beta \tag{38}$$

$$\dot{\beta} = \frac{V_T}{\rho} \tag{39}$$

Force equations: $$\lambda = M_F \left[\frac{V_T^2}{\rho} - (\overline{e}_{N_o} \cdot \overline{A}_a)\right] \tag{40}$$

$$f = \mu |\lambda| + \eta |V_T| \quad ; \quad \mu , \eta \geq 0 \tag{41}$$

$$FY = f \cos\beta + \lambda e_{N_{o_j}} - A_j M_s \tag{42}$$

$$FZ = f \sin\beta + \lambda e_{N_{o_k}} - A_k M_s \tag{43}$$

$$MX = (f \sin\beta + \lambda e_{N_{o_k}}) Y - (f \cos\beta + \lambda e_{N_{o_j}}) Z \tag{44}$$

Additional equations: $$\rho = \mathrm{ABS} \left[\frac{\left[1 + \left(\frac{dY}{dZ}\right)^2\right]^{3/2}}{\frac{d^2Y}{dZ^2}}\right] \tag{45}$$

$$Z = \left[\frac{1}{\frac{c^2}{a}\ \text{TAN}^2\beta + c}\right]^{\frac{1}{2}} \tag{46}$$

$$Y = \left[\frac{1 - cZ^2}{a}\right]^{\frac{1}{2}} \tag{47}$$

$$R = \left[Y^2 + Z^2\right]^{\frac{1}{2}} \tag{48}$$

$$\Phi = \text{ARCTAN}\left(\frac{Z}{Y}\right) \tag{49}$$

B. COMPUTER PROGRAM: LAMPS (LARGE AMPLITUDE SLOSH)

The equations presented in the previous section have been implemented for computer solution. The program, LAMPS, has been written in Fortran IV compatible with the MSFC Univac 1108. Several subroutines from the existing FORMA (Reference 4) library at MSFC have been used in addition to those developed under this contract. LAMPS provides time history plots of forces for comparison to test data in addition to detailed printouts of state and position variable time histories which track the liquid cm as it moves through the tank.

1. General Comments on the Computer Simulation - Figure III-5 delineates the general motion of the liquid cm through the tank on the constraint surface.

The liquid travels on elliptical segments that approximate the constraint surface. When the cm deviates from the constraint surface more than an allowed distance, the ellipse is updated in order to return the cm to the constraint surface. The criteria for updating is expressed as follows:

$$\text{ABS}\ (R(cm) - R(cs)) > \left(\frac{(\text{CRIT})\,(R(cs))}{100\%}\right) \tag{50}$$

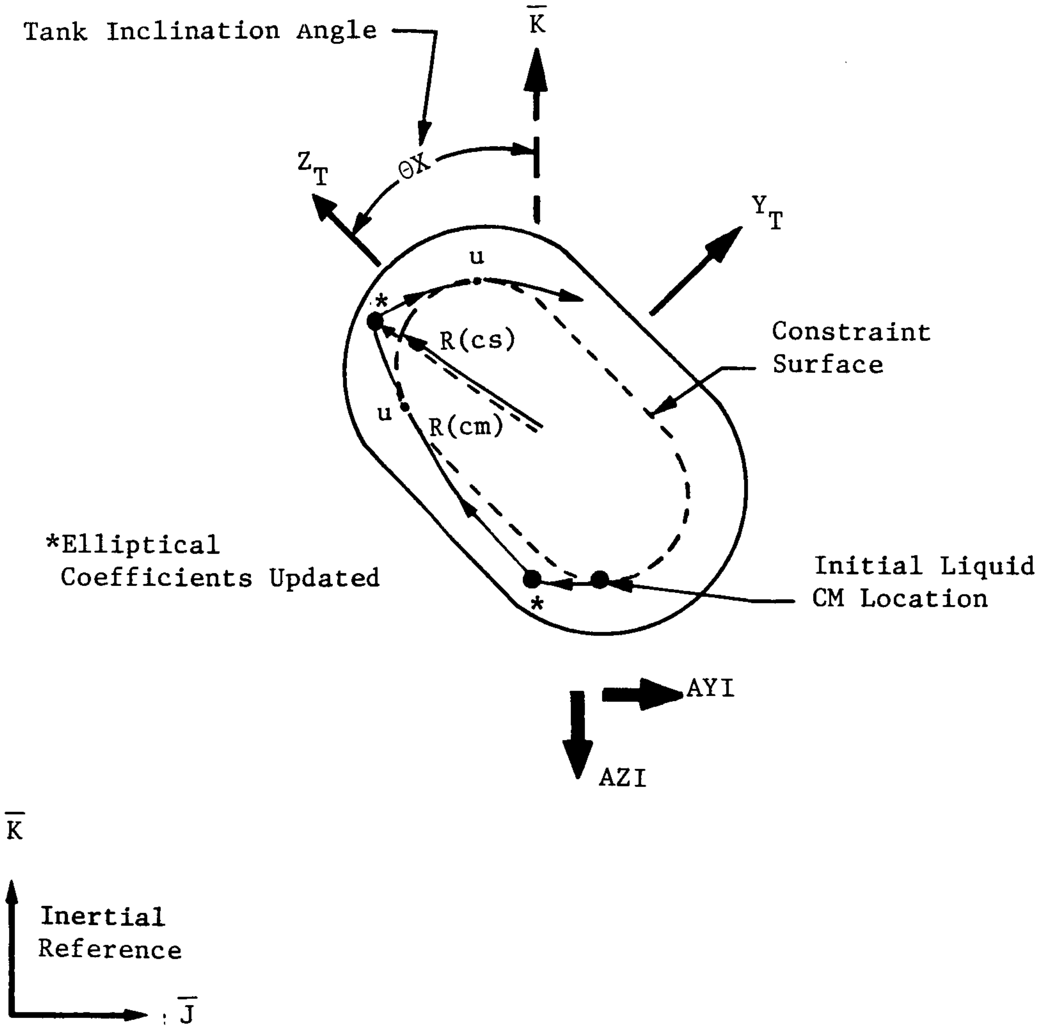


FIGURE III-5. MOTION OF LIQUID CM IN COMPUTER SIMULATION (EXAGGERATED)

where: R(cm) = distance from the tank coordinate system origin to the fluid cm (Figure III-5)

R(cs) = distance from the tank coordinate system origin to the constraint surface based on the fluid cm's current Φ (Figure III-5)

CRIT = input criteria to the program expressing the percent allowable deviation from the constraint surface based on distance R(cs).

If this inequality is satisfied, the ellipse approximating the constraint surface is updated. The update is performed using the current fluid cm location and a point on the constraint surface in the direction of fluid motion (represented by points labeled "u" in Figure III-5). In matrix notation, the updated elliptical coefficients, a and c, are defined as follows from the general equation for the ellipse (equation 26):

$$\begin{Bmatrix} a \\ c \end{Bmatrix} = \begin{bmatrix} y(cm) & z(cm) \\ y(u) & z(u) \end{bmatrix}^{-1} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \tag{51}$$

The applied accelerations, AYI and AZI, initiate and maintain the motion of the fluid cm. These accelerations may be input to the program as constants or as functions of time. The only restriction to the input values is that AYI must not equal zero at time zero. If AYI is zero at time zero, the fluid cm will not move and the program will terminate execution.

2. Components of the Simulation Program - Figure III-6 presents a general flow chart of program LAMPS. The function of the subroutines used in LAMPS is detailed below.

SURF: Defines the constraint surface table by analytically rotating the tank in a one-g field and storing the position of the fluid cm. The tank is assumed axis-symmetric, hence, SURF only rotates the tank through 90°. The table is stored as values of R(cs) for given Φ values (calls FLUDCG).

FLUDCG: Defines the initial fluid cm location (tank body system) assuming AYI = 0. g, AZI = 1. g, and accounting for tank inclination angle θX. FLUDCG works for general cylindrical tanks with hemi-ellipsoidal domes; i.e., in the limit cylindrical tanks and spherical tanks. A planar free fluid surface is assumed and FLUDCG moves this surface around until the calculated fluid volume (through numerical integration) equals the desired fluid volume within a given tolerance. The free surface is always aligned parallel to the inertial plane, I-J (Figure III-5).

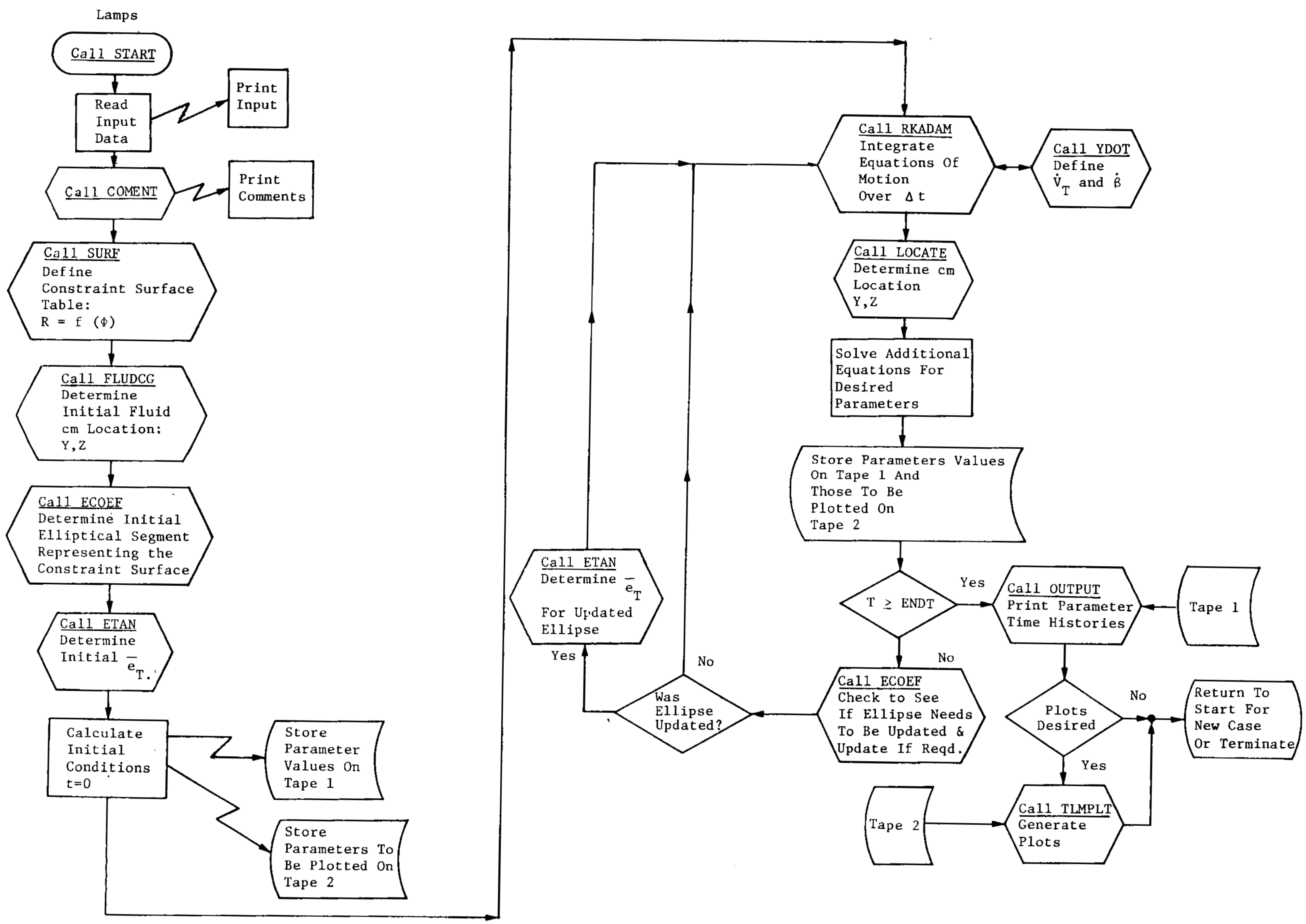


Figure III-6. General Flow Chart of LAMPS

ECOEF: Determines the ellipse which best approximates the constraint surface in the region of the fluid cm. ECOEF also checks to see if the ellipse needs updating based on the update criteria and updates if required.

ETAN: Defines the instantaneous unit tangent vector, $\bar{e}_T$, to the elliptical approximation of the constraint surface.

LOCATE: Determines the location of the fluid cm, y and z, after the fluid begins to move. The location is determined from the surface equation (equation 26) and equation(30)as shown in equations (27) and (32).

YDOT: Defines the derivatives of the state variables, V_T and β , for use in the integration routine.

RKADAM: Integrates the equations of motion (defined in YDOT) using a fourth order Runge Kutta (Gill modification) algorithm.

IQUAD: Fortran Function which determines the quadrant of β .

OUTPT: Prints the results of the analytic simulation at the time increments specified.

TLMPLT: On option, plots time histories if V_T, $\dot{V}_T$, β , $\dot{\beta}$, Φ , FY, FZ, and MX. In addition, TLMPLT plots the fluid travel through the tank, Z vs Y.

In addition to the above subroutines, which were written under this contract, the following FORMA (Reference 4) subroutines are also used: COMENT, INV5, PAGHED, PLOT1, PLOTSS, READ, SMEQ1, START, TERP1, TERP2, VCROSS, VDOT, WRITE and ZZBOMB.

3. Input Format - The input format for LAMPS is defined below as well as the definitions of the input and output variables. Sample input and output as well as a program listing are provided in Appendix B.

```
C*********************************************************************LAS
C  INPUT FORMAT                                                        LAS
C  ------------                                                        LAS
C1000 READ(A6,I4,3A6) RUNNO,UNAME                                      LAS
C     IF(RUNNO.EQ.4HSTOP)STOP                                          LAS
C     READ(12A6)        TITLE1                                         LAS
C     READ(12A6)        TITLE2                                         LAS
C     READ(6E10.3)      XL,TR,TD,PCVOL,THETAX,FDEN                     LAS
C     READ(6I5)         NR,NTHET,NTABLE,IPRINT,NPRINT,NPLOT            LAS
C     READ(4E10.3)      VXX,CRIT,DELTAT,ENDT                           LAS
C     READ(4E10.3)      AYI,AZI,XMU,XNU,SMASS                          LAS
C     CALL COMENT       COMMENT CARDS, LAST CARD 10 ZEROS COLUMNS 1-10 LAS
C     IF(AZI.EQ.999..OR.AYI.EQ.999.)CALL READ(ACCEL,NA,NC,K1,3)        LAS
C     IF(NTABLE.LE.0)CALL READ(TABLE,NTABLE,NCT,K1,2)                  LAS
C     GO TO 1000                                                       LAS
C                                                                      LAS
C                                                                      LAS
C  DEFINITION OF INPUT VARIABLES                                       LAS
C  -----------------------------                                       LAS
C  RUNNO  = RUN NUMBER PRINTED IN PAGE HEADING.                        LAS
C  TITLE1 = TITLE CARD PRINTED IN PAGE HEADING.                        LAS
C  TITLE2 = TITLE CARD PRINTED IN PAGE HEADING.                        LAS
C  XL     = LENGTH OF PROPELLANT TANK CYLINDRICAL SECTION. (L UNITS)   LAS
C  TR     = TANK RADIUS. (L UNITS)                                     LAS
C  TD     = HEIGHT OF TANK DOME FROM TOP OF CYLINDRICAL SECTION. (L UNITS)  LAS
C  PCVOL  = PERCENTAGE TANK FILL .LE. 100.                             LAS
C  THETAX = ANGLE TANK IS ROTATED ABOUT X-AXIS IN INERTIAL TRIAD. (DEGREES)  LAS
C  FDEN   = PROPELLANT DENSITY. (F UNITS*SEC**2/L UNITS**4)            LAS
C  NR     = NUMBER OF RADIAL INTEGRATION INCREMENTS ON TANK RADIUS FOR LAS
C           DETERMINING TANK CG, SUGGEST NR= 50.                       LAS
C  NTHET  = NUMBER OF ANGULAR INTEGRATION INCREMENTS AROUND TANK       LAS
C           CIRCUMFERENCE FOR DETERMINING TANK CG, SUGGEST NTHET= 50.  LAS
C  NTABLE = 0, READ IN A TABLE DESCRIBING CONSTRAINT SURFACE (PHI VS R).  LAS
C         = N, LAMPS WILL DEFINE AN AXIS-SYMMETRIC CONSTRAINT SURFACE  LAS
C              TO BE STORED IN A TABLE AS PHI VS R WITH NTABLE VALUES  LAS
C              OF PHI FROM 0 TO 90 DEG. (N.GT.0.LE.20.)                LAS
C  IPRINT = 1, NORMAL PRINTOUT.                                        LAS
C           2, FULL CHECKOUT PRINTOUT.                                 LAS
C  NPRINT = LAMPS WILL PRINT EVERY NPRINT(TH) TIME POINT.              LAS
C  NPLOT  = 0, NO PLOTS WILL BE GENERATED.                             LAS
C         = 1, GENERATE TIME HISTORY PLOTS OF VTDOT,VT,BETADOT,BETA,   LAS
C              FY,FZ,MX AND FLUID POSITION Y VS Z.                     LAS
C  VXX    = ITERATION CUTOFF (PERCENT FLUID VOLUME) FOR INITIAL CALCULAT-  LAS
C           ION OF FLUID CG, SUGGEST VXX= 2.0.                         LAS
C  CRIT   = UPDATE CRITERIA , PERCENTAGE DEVIATION FROM R(TABLE) ALLOWED.  LAS
C           IF /R(ACTUAL)-R(TABLE)/.GT.(CRIT*R(TABLE)/100.) UPDATE.    LAS
C  DELTAT = TIME INCREMENT FOR INTEGRATING THE EQUATIONS OF MOTION.(SEC)  LAS
C  ENDT   = TIME CUTOFF FOR PROGRAM TERMINATION. (SEC)                 LAS
C  AYI    = APPLIED Y ACCELERATION IN INERTIAL TRIAD.(L UNITS/SEC**2)  LAS
C           MUST NOT EQUAL 0.                                          LAS
C         = 999.,READ IN TIME HISTORY ACCELERATION TABLE.(ACCEL)       LAS
C  AZI    = APPLIED Z ACCELERATION IN INERTIAL TRIAD.(L UNITS/SEC**2)  LAS
C         = 999.,READ IN TIME HISTORY ACCELERATION TABLE.(ACCEL)       LAS
C  XMU    = COEF. WHICH RELATES FRICTION FORCE TO INERTIAL FORCE.(N.D.)  LAS
C  XNU    = COEF. WHICH RELATES FRICTION FORCE TO CENTER OF MASS       LAS
C           VELOCITY. (F UNITS*SEC/L UNITS)                            LAS
C  SMASS  = STRUCTURAL MASS ASSUMED INERT AT CENTER OF TANK TRIAD.     LAS
C           SMASS IS TANK STRUCTURE MASS AND IS USED IN CALCULATING    LAS
C           FORCES FOR COMPARISON WITH TEST DATA.(F UNITS*SEC**2/L UNITS)  LAS
C  ACCEL  = MATRIX OF ACCELERATION TIME HISTORIES READ IF EITHER AYI OR  LAS
C           AZI.EQ.999. OTHER VALUES OF EITHER AYI OR AZI WILL OVERRIDE  LAS
C           TABLE VALUES. MATRIX IS AN NA X 3 ,COLUMN 1 IS TIME (SEC),  LAS
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
C           COLUMN 2 IS AYI, COLUMN 3 IS AZI (L UNITS/SEC**2). NA.LE.20.         LAS
C           AYI MUST NOT EQUAL 0. AT TIME= 0.                                   LAS
C  TABLE  = CONSTRAINT SURFACE TABLE  NTABLE X 2 . NTABLE DEFINED IN           LAS
C           CALL READ. COLUMN 1 IS CENTER OF MASS LOCATION PHI (DEGREES),       LAS
C           COLUMN 2 IS CORRESPONDING DISTANCE FROM TANK TRIAD ORIGIN           LAS
C           R (L UNITS). NTABLE.LE.20.                                          LAS
C                                                                               LAS
C                                                                               LAS
C                                                                               LAS
C  DEFINITION OF OUTPUT PARAMETERS                                              LAS
C  -------------------------------                                              LAS
C  TIME    = SIMULATION TIME. (SEC)                                             LAS
C  VTDOT   = FLUID CM ACCELERATION. (L UNITS/SEC**2)                            LAS
C  VT      = FLUID CM VELOCITY. (L UNITS/SEC)                                   LAS
C  BETADOT= ANGULAR VELOCITY OF VELOCITY VECTOR. (DEGREES/SEC)                  LAS
C  BETA    = ANGLE THE VELOCITY VECTOR MAKES WITH THE TANK TRIAD Y AXIS         LAS
C            (DEGREES.GE.0.,LE.360.)                                            LAS
C  X,Y,Z   = FLUID CM LOCATION IN TANK TRIAD. (L UNITS)                         LAS
C  R       = RADIAL DISTANCE FROM TANK TRIAD ORIGIN TO FLUID CM. (L UNITS)      LAS
C  PHI     = FLUID CM LOCATION AS ANGLE MEASURED FROM TANK TRIAD Y AXIS         LAS
C            TO RADIAL VECTOR R. (DEGREES)                                      LAS
C  AY,AZ   = APPLIED ACCELERATIONS AYI AND AZI TRANSFORMED TO THE TANK          LAS
C            TRIAD. (L UNITS/SEC**2)                                            LAS
C  ACO,CCO= COEFS. IN ELLIPTICAL SURFACE EQUATION FOR THE ELLIPTICAL            LAS
C            SEGMENT REPRESENTING THE CONSTRAINT SURFACE. (N.D.)                LAS
C            ACO*Y**2+CCO*Z**= 1.0                                              LAS
C  RHO     = RADIUS OF GYRATION OF THE ELLIPTICAL SURFACE AT X,Y,Z.             LAS
C            (L UNITS)                                                          LAS
C  TANGENT= J AND K ARE COMPONENTS OF THE INSTANTANEOUS UNIT TANGENT            LAS
C            VECTOR WHICH IS THE DIRECTION OF THE VELOCITY VECTOR. (N.D.)       LAS
C  NORMAL  = J AND K ARE COMPONENTS OF THE INSTANTANTANEOUS UNIT NORMAL         LAS
C            VECTOR TO THE ELLIPTICAL SEGMENT. (N.D.)                           LAS
C  FY,FZ   = FORCES EXERTED ON TANK SUPPORTS DUE TO FLUID MOTION AND TANK       LAS
C            STRUCT.  INERTIAL FORCES, IN TANK TRIAD. (F UNITS)                 LAS
C  MX      = MOMENT EXERTED ON TANK SUPPORTS DUE TO FLUID MOTION, IN            LAS
C            TANK TRIAD. (L UNITS*F UNITS)                                      LAS
C  KEY1    = 0, MODEL FREE TO UPDATE ELLIPTICAL SURFACE AT WILL.                LAS
C            1, LAST UPDATE PERFORMED UNTIL BETA ENTERS A NEW QUADRANT.         LAS
C               FLUID CM IS OUTSIDE TANGENT TO CONSTRAINT SURFACE AT            LAS
C               AXIS INTERCEPT, HENCE NO UPDATE IS PERFORMED.                   LAS
C          = 2, LAST UPDATE PERFORMED UNTIL BETA ENTERS A NEW QUADRANT.         LAS
C               FLUID CM EXCEED CRIT CRITERIA AND IS WITHIN 20 DEGREES          LAS
C               OF AN AXIS INTERCEPT.                                           LAS
C          = 3, LAST UPDATE PERFORMED UNTIL BETA ENTERS A NEW QUADRANT.         LAS
C               FLUID CM EXCEEDS CRIT CRITERIA BUT IS WITHIN 1 DEG OF           LAS
C               AXIS INTERCEPT, HENCE NO UPDATE IS PERFORMED.                   LAS
C  KEY2    = 0, NO UPDATE WAS PERFORMED AT LAST TIME POINT.                     LAS
C          = 1, UPDATE WAS PERFORMED AT LAST TIME POINT.                        LAS
C  NQB     = QUADRANT OF THE ANGLE BETA.(1,2,3,4)                               LAS
C  NQF     = QUADRANT OF THE ANGLE PHI.(1,2,3,4)                                LAS
C                                                                               LAS
C                                                                               LAS
C NOTES                                                                         LAS
C -----                                                                         LAS
C  1) THE UNITS OF THE OUTPUT PARAMETERS ARE DEPENDANT ON THE UNITS OF          LAS
C     THE INPUT PARAMETERS. EITHER METRIC OR ENGLISH UNITS MAY BE USED.         LAS
C                                                                               LAS
C  2) L UNITS - LENGTH UNITS, IN,FT,METERS,CM, ETC.                             LAS
C     F UNITS - FORCE UNITS, LB,KG,GRAMS, ETC.                                  LAS
C     ALL TIME UNITS ARE SECONDS.                                               LAS
C     ALL ANGLE UNITS ARE DEGREES.                                              LAS
C                                                                               LAS
```

```
C   3) ZZBOMB ERRORS-                                                         LAS
C        NERROR=1, SUBROUTINE FLUDCG FAILED TO CONVERGE.                      LAS
C              2, AYI= 0. AT TIME= 0.                                         LAS
C                                                                             LAS
C   4) SUBROUTINES CALLED BY LAMPS-- SURF,FLUDCG,ECOEF,ETAN,LOCATE,YDOT,      LAS
C        RKADAM,IQUAD,OUTPT,TLMPLT .                                          LAS
C       FORMA SUBROUTINES-- COMENT,INV5,PAGEHD,PLOT1,PLOTSS,READ,SMEQ1,       LAS
C        START,TERP1,TERP2,VCROSS,VDOT,WRITE,ZZBOMB .                         LAS
C                                                                             LAS
C                                                                             LAS
C*****************************************************************************LAS
```

IV. TEST/ANALYTICAL CORRELATION

This chapter presents a discussion of the test results and provides a comparison of analytical predictions with test data. Appendix C presents all measured force time histories along with those generated by the digital simulation (Program LAMPS) assuming no viscous dissipative force. In addition, Appendix C includes a test log which delineates any problems associated with individual tests and a qualitative appraisal of their worth.

A. OBSERVATIONS ON LIQUID MOTION

The motion of the liquid observed in the tests adds to the basic understanding of the manner in which the liquid moves during propellant reorientation in a tank. In some of the early work in this area (Reference 5), the applied acceleration was purely axial. When the liquid interface was initially flat, it was found that if the Bond number was less than 10, the liquid reoriented along the tank walls. If the Bond number was greater than 10, an instability formed in the center of the interface. This instability has the form of a cylindrical column that travels through the center of the tank to the opposite end. This phenomena was studied in further detail (Reference 6) by tilting the tank slightly off-axis from the applied acceleration. These tests demonstrated that the instability will join the wall flow when the misalignment of the acceleration and tank is as small as one degree. When the initial interface is highly curved, it was found that the central instability did not form over a range of Bond numbers from 3 to 450 (References 7 and 8).

In the tests performed for this study, the potential for the formation of the central instability was present since the Bond number was large and the initial interface was flat. Two factors were introduced into the tests to prevent the instability from fully forming. First, the tank was oriented at an angle to the axial acceleration for most of the tests (the tank was oriented axially for some of the tests). Hence, an effect similar to that observed by Bowman (Reference 6) was expected, in that the lack of symmetry causes the instability to be displaced toward the tank wall. Surface tension appears to be the force that causes this displacement of the instability. In addition, a lateral acceleration that acted perpendicular to the axial acceleration was always applied. In some of the tests the slider did not function properly and rather than applying a lateral acceleration, only a short duration lateral pulse was applied; this pulse was sufficient to produce the desired fluid motion; namely, the fluid adhered to the tank wall during reorientation.

In every test the liquid reoriented along the tank wall, regardless of the tank orientation and magnitude of the lateral acceleration. For some tests, initial formation of an instability could be observed (Figure IV-1,3). However, it quickly joined the flow of liquid along the wall and disappeared. The leading edge of the flow adhered strongly to the tank wall, following the wall as it encircled the tank. Apparently, a small lateral acceleration occurring as the liquid first begins to move is all that is required to keep the liquid moving along the wall throughout the reorientation.

As the liquid began to move, the fluid interface remained relatively flat so the motion appeared as a rotation of the interface about the tank center. Once the leading edge of the flow reached the tank dome, the fluid interface began to acquire some curvature. The liquid, in general, overshot its final equilibrium position, continuing on around the tank, recirculating a small percentage of the liquid. Very little splashing of the liquid was observed, and the leading edge of the liquid remained attached to the tank wall. During the test time available, the liquid was observed to reorient, overshoot the equilibrium position and come to a halt. Subsequent damped oscillation of the liquid about its equilibrium position could not be observed due to test time limitations.

A typical test is shown in Figure IV-1. This is test number 8 in which the liquid volume was 50%, the tank was inclined at 60^{o} and the smaller of the two axial accelerations was applied to the tank.

When the liquid volume was 75%, the reorientation of the liquid was similar to that described above, except that the ullage assumed the form of a bubble and moved to the opposite end of the tank. The bubble followed the tank wall as it moved. Its surface was highly irregular due to the flow of liquid about the bubble. At the end of the test the bubble had become somewhat flattened and the center of gravity of the liquid had overshot the equilibrium position.

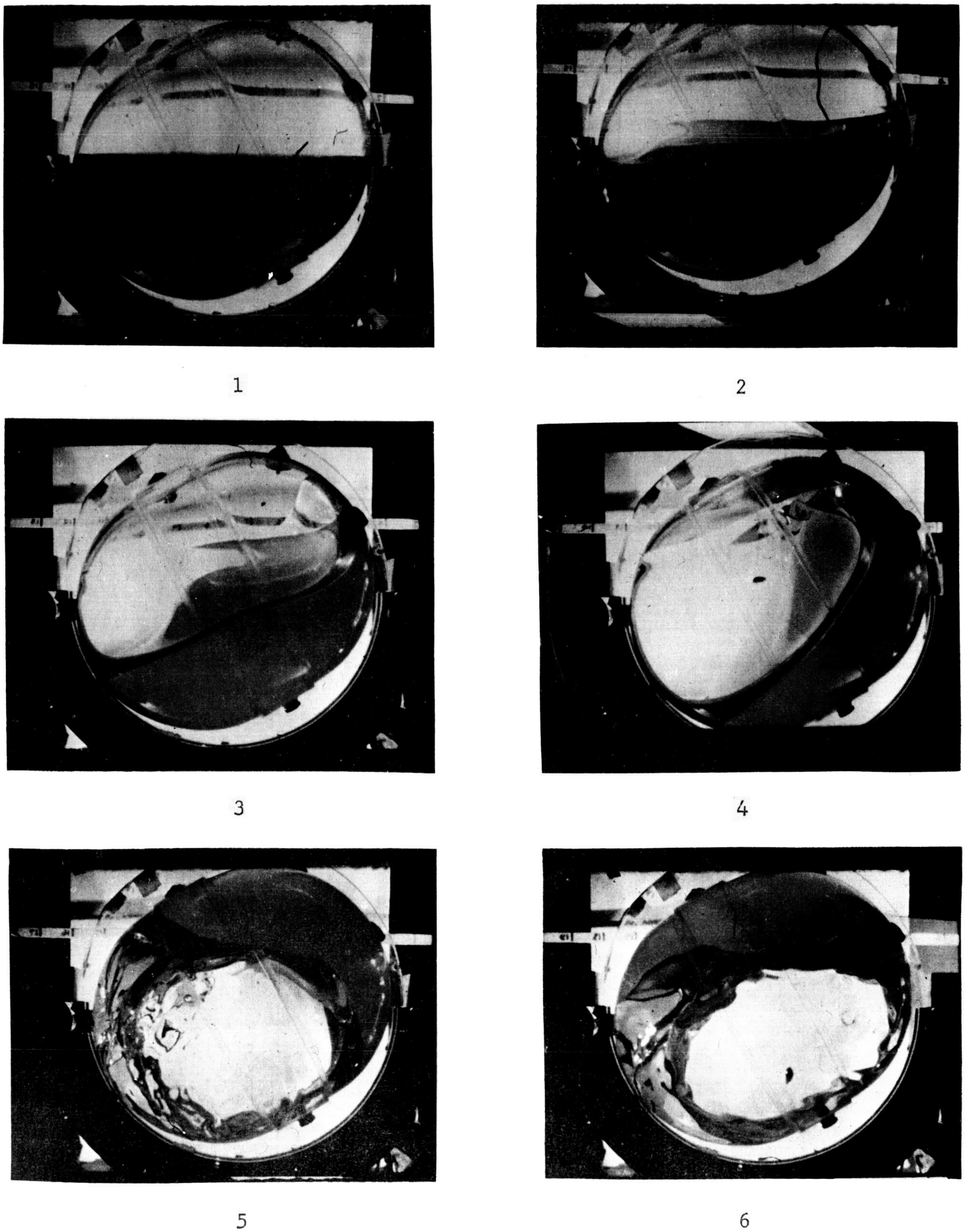


Figure IV-1. Typical Fluid Reorientation; Test 8, 50% Fill, 60° Tank Inclination, A_a = .045g

With the manner of reorientation produced in these tests, a geyser did not form at the reoriented position of the liquid. Geyser formation was categorized in Reference 7 for purely axial acceleration. This is another phenomena of propellant reorientation that is eliminated by a slight off-axis disturbance to the liquid flow.

As the reoriented liquid meets the top of the tank due to a purely axial acceleration, a geyser may be formed that travels through the center of the tank. Liquid is returned to the bottom of the tank by this geyser. The conditions under which a geyser would be expected were categorized in Reference 7. No geyser was observed in any of the tests conducted for this program. The lateral acceleration caused the liquid to flow along one side of the tank, eliminating the joining of the flow at the top of the tank that causes geyser formation.

B. DISCUSSION OF TEST/ANALYTICAL CORRELATION

In general, it is felt that the forces measured during the drop testing are valid. However, due to the small liquid mass and low acceleration levels in the test, force resolution was a definite problem. A study of the test results shows that much better force definition was obtained with the larger axial acceleration. Lateral forces were much smaller than axial forces due to the 1-g axial load relief at drop initiation and the larger axial accelerations applied. Hence, the lateral load cell (#1, Figure II-6) was set at a very high sensitivity in order to resolve these small forces. This high sensitivity increased the susceptability of the lateral load cell to vibrations due to bearing noise, support structure vibrations, etc. Some of this noise was reduced or eliminated by digital filtering as discussed in Chapter I. This noise is most evident in FY for a tank inclination of 0°, and FZ for a tank inclination of 90°. For other tank inclinations the noise is masked by the relatively large axial loads.

The moment, MX, calculated from measured forces is highly suspect due to the small differences between load cells. Small errors can completely change the sign and character of the measured moment. It is felt that more meaningful comparisons can be made between test and analytical forces (FY, FZ) than between test and analytical values for MX.

Figures IV-2 through IV-7 present comparisons of test data and analytical predictions (FY, FZ) for the large axial acceleration ($\approx$.09g) and a tank inclination of 0^{o}. Comparisons are shown for liquid fill volumes of 10%, 25%, 50% and 75%. In addition, comparisons of measured and predicted moment, MX, are shown in Figures IV-4 and IV-6. Figure IV-8 shows comparisons for 25% liquid fill and a tank inclination of 45^{o}.

In general, the character of the predicted and measured force time histories are similar. Predicted values of the force time histories were run assuming several values for η (Chapter III, equation 25); μ was always assumed to be zero. A study of the comparisons indicates that the assumed form for the viscous dissipative force (equation 25) is not optimal for the simulation. As mentioned in Chapter III, the form of this force is not well known. An in-depth investigation into its form was beyond the scope of this study, however, indications are that it may be non-linear.

Observation of the presented comparisons shows that the predicted force time histories, trend-wise match the measured time histories. Although, in general, predicted forces are of higher magnitude than those measured. Increasing η reduces the predicted magnitude but also induces time lag which degrades correlation. Two possible model improvements will most likely improve correlation. The first is an improved form for the viscous dissipative force as discussed above. The second is the relieving of the constraint that the fluid cm must always follow the constraint surface. In the initial moments of the drop, the observed instability (Section A of this chapter) indicates that the liquid cm actually follows a trajectory interior to the assumed constraint surface. Incorporation of this capability of trajectory travel and improved viscous force definition would intuitively improve timing and force level correlation.

The analytic simulation appears to work best for smaller liquid fill volumes. This may be intuitive as per the discussion of liquid motion in Section A of this chapter. The simulation assumes that the fluid is a point mass moving on a constraint surface obtained by slow rotation of the tank maintaining a flat liquid interface. In large fill volumes (i.e., 75%) the liquid motion was more characterized by a moving ullage bubble. This is evident in the rigid body type forces that were measured as shown in Figure IV-7. Liquid motion observed for fill volumes from 10% to 50% was more representative of that assumed in the simulation (see Figure IV-1).

The liquid cm location can also be used in correlating test and prediction data. LAMPS provides time history cm position data which can be compared to scaled photographic records of the tests. In general, liquid cm location time history correlation was good and indicated the need for some viscous dissipative force to keep the fluid from completely circulating in some simulation cases. See Appendix B for sample plots generated by LAMPS.

Overall applicability of the analytical model is considered to be good. It is felt that improved correlation is possible with further study of the nature of the dissipative force and improvements in the allowed liquid trajectories. The test results are also considered good and it is felt that the measured forces are valid comparators for the analytical model within a reasonable degree of accuracy.

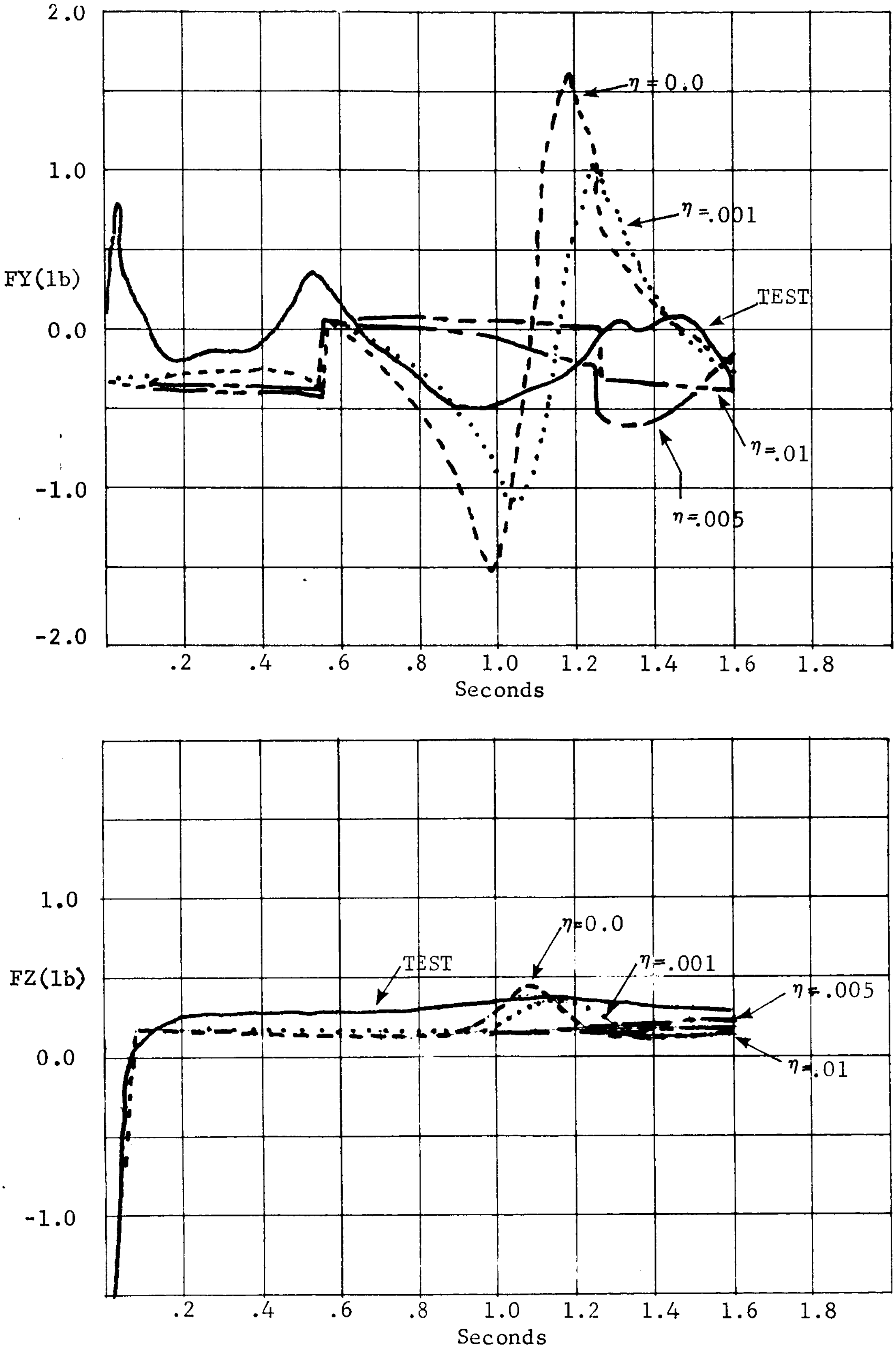
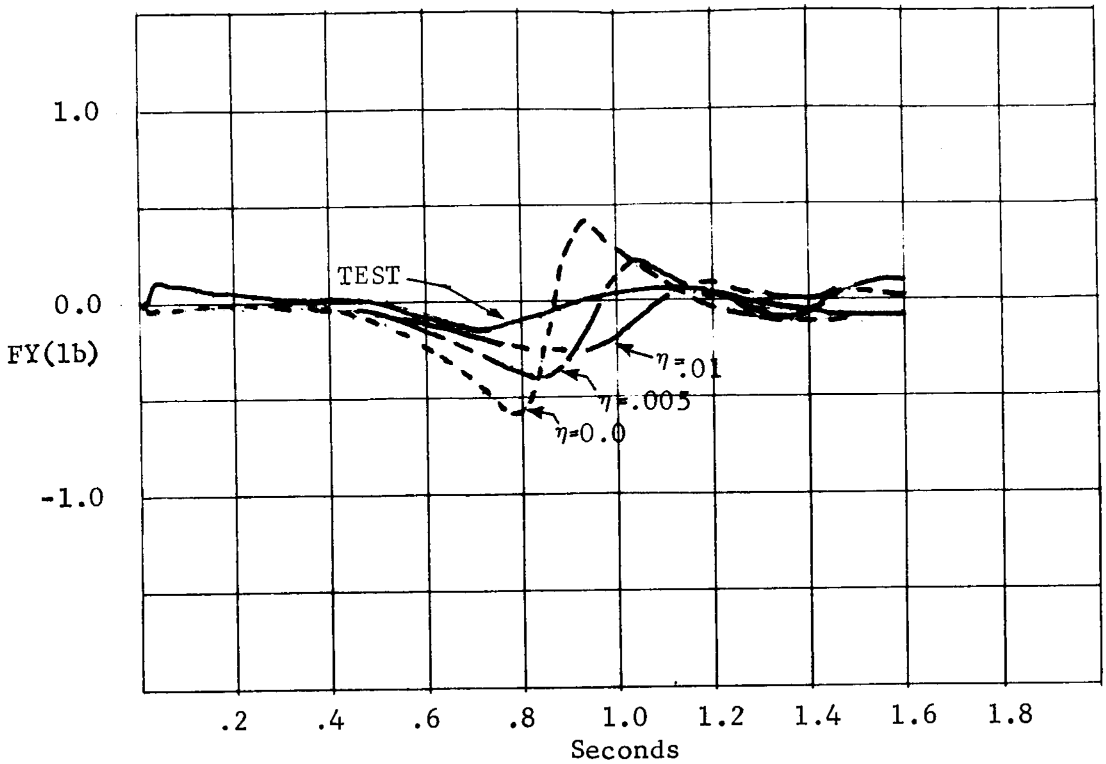


FIGURE IV-2. TEST 22, $\theta X = 0^{o}$, 10% FILL, A_a = .09g



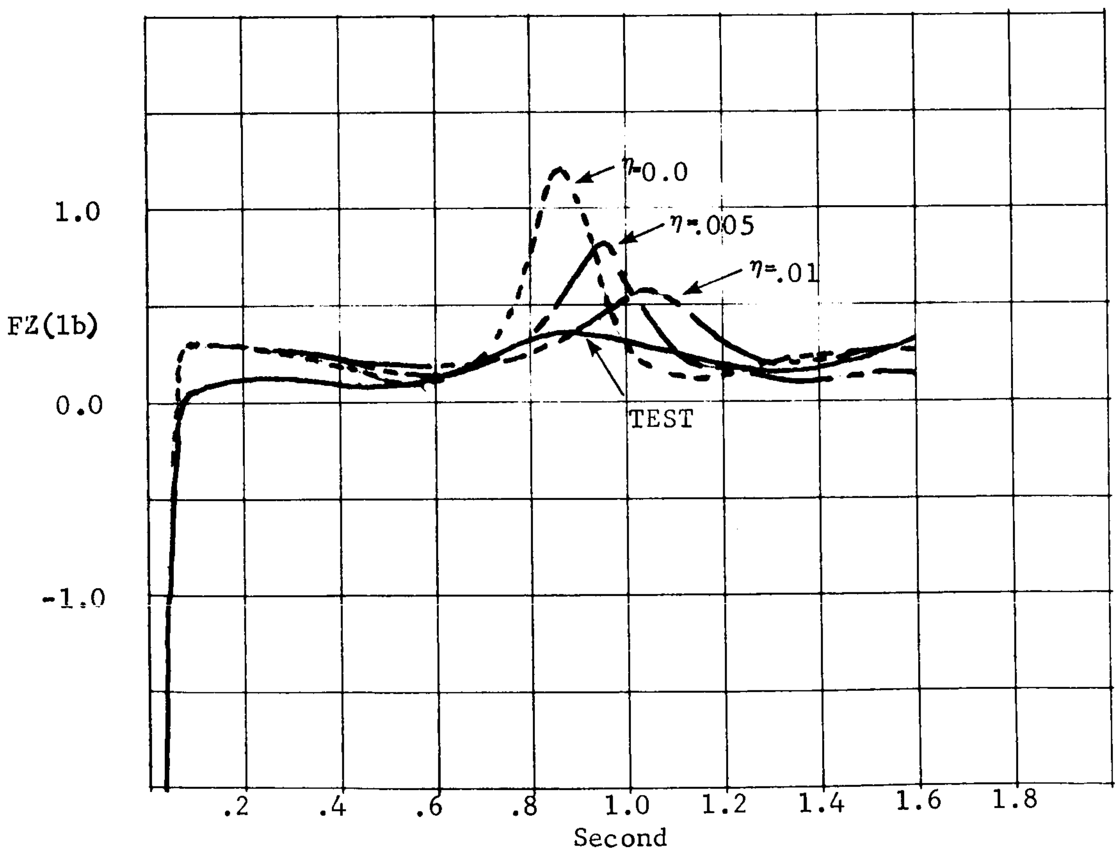


FIGURE IV-3. TEST 13, $\theta X = 0^{o}$, 25% FILL, A_a = .09g

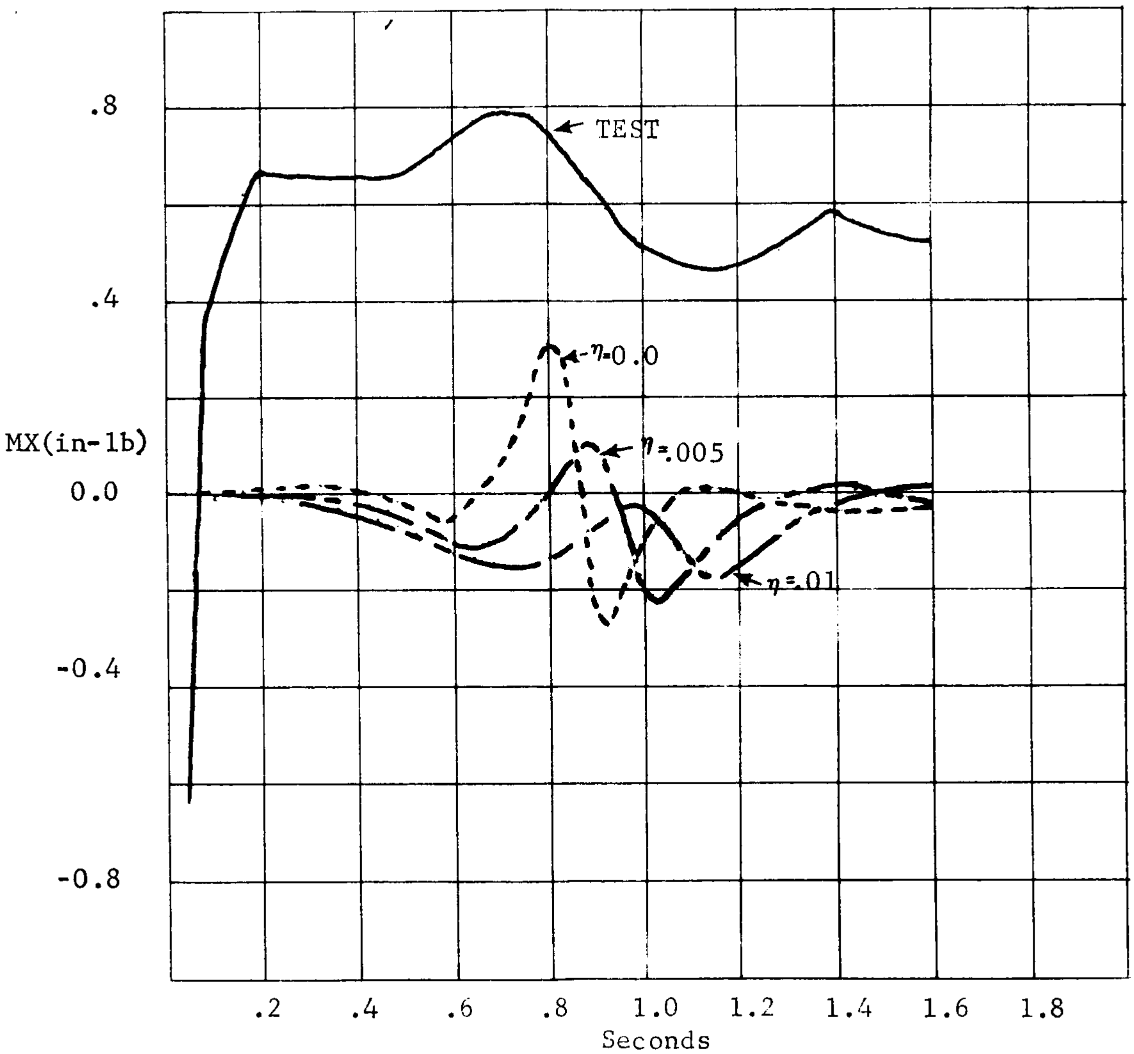
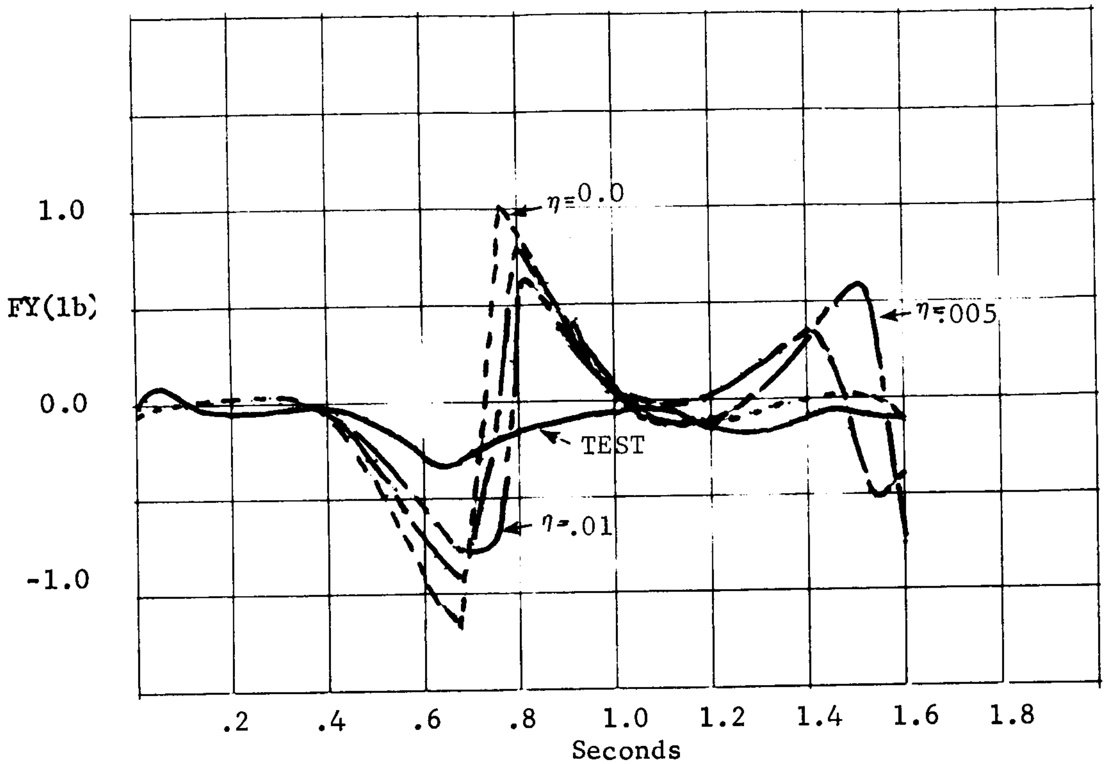


FIGURE IV-4. TEST 13, $\theta X = 0^{\circ}$, 25% FILL, A_a = .09g



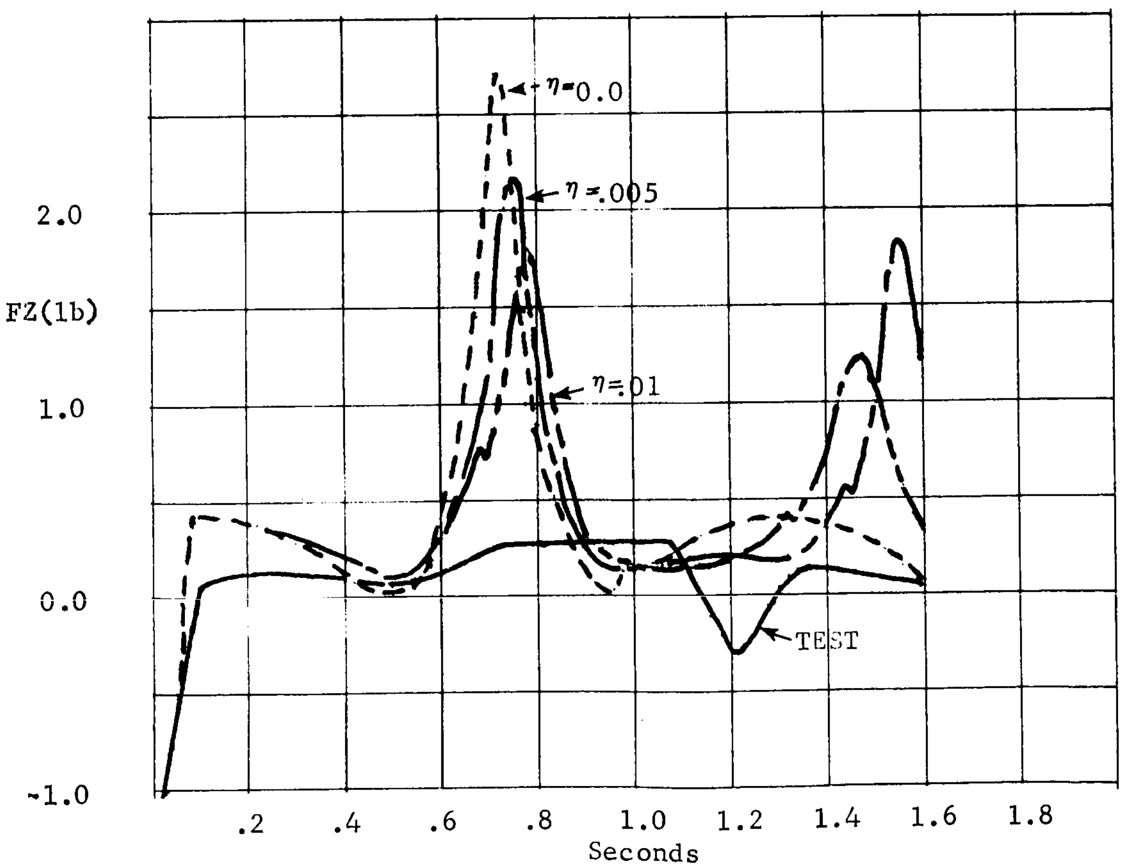


FIGURE IV-5. TEST 14, $\theta X = 0^{\circ}$, 50% FILL, A_a = .09g

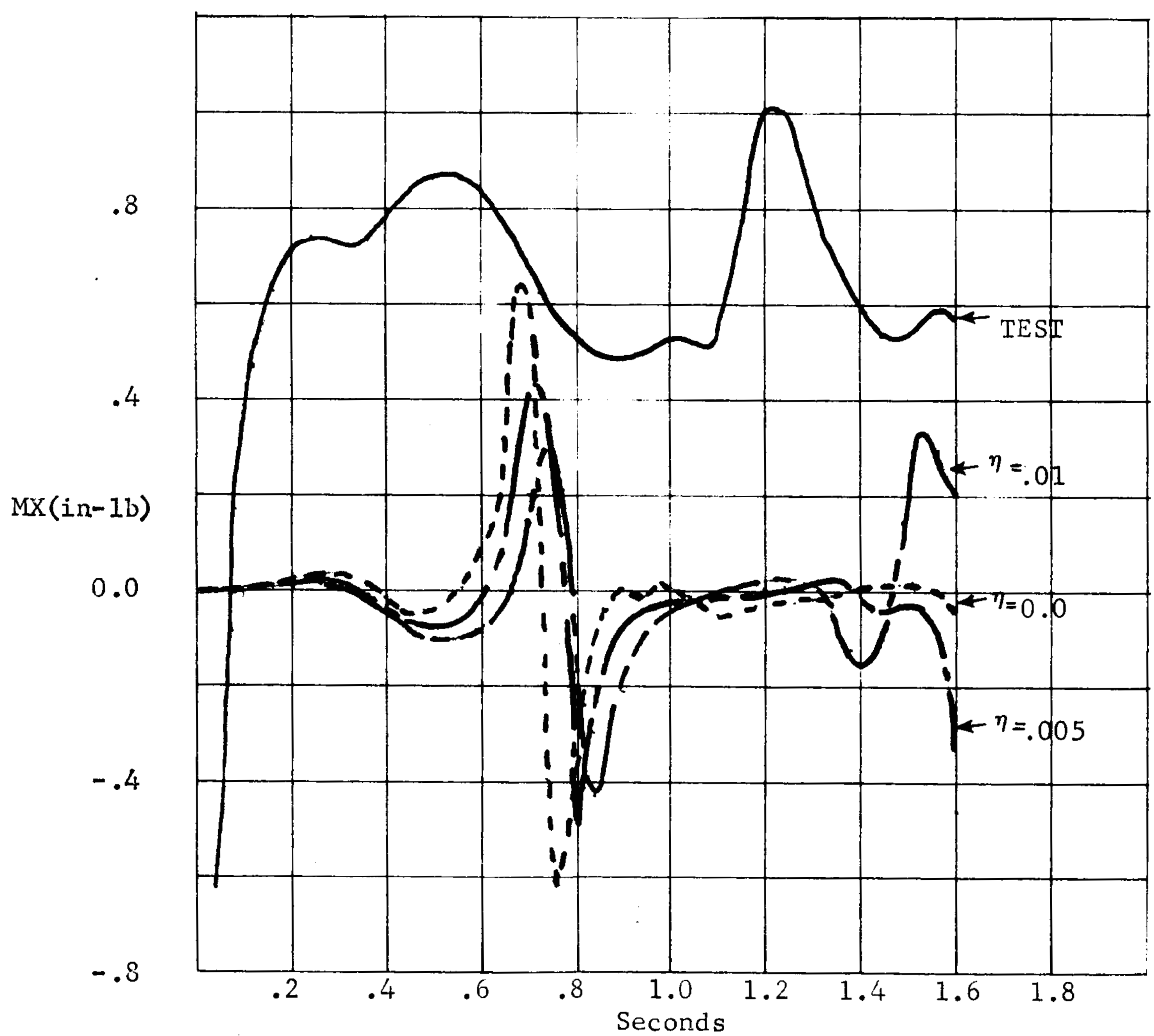
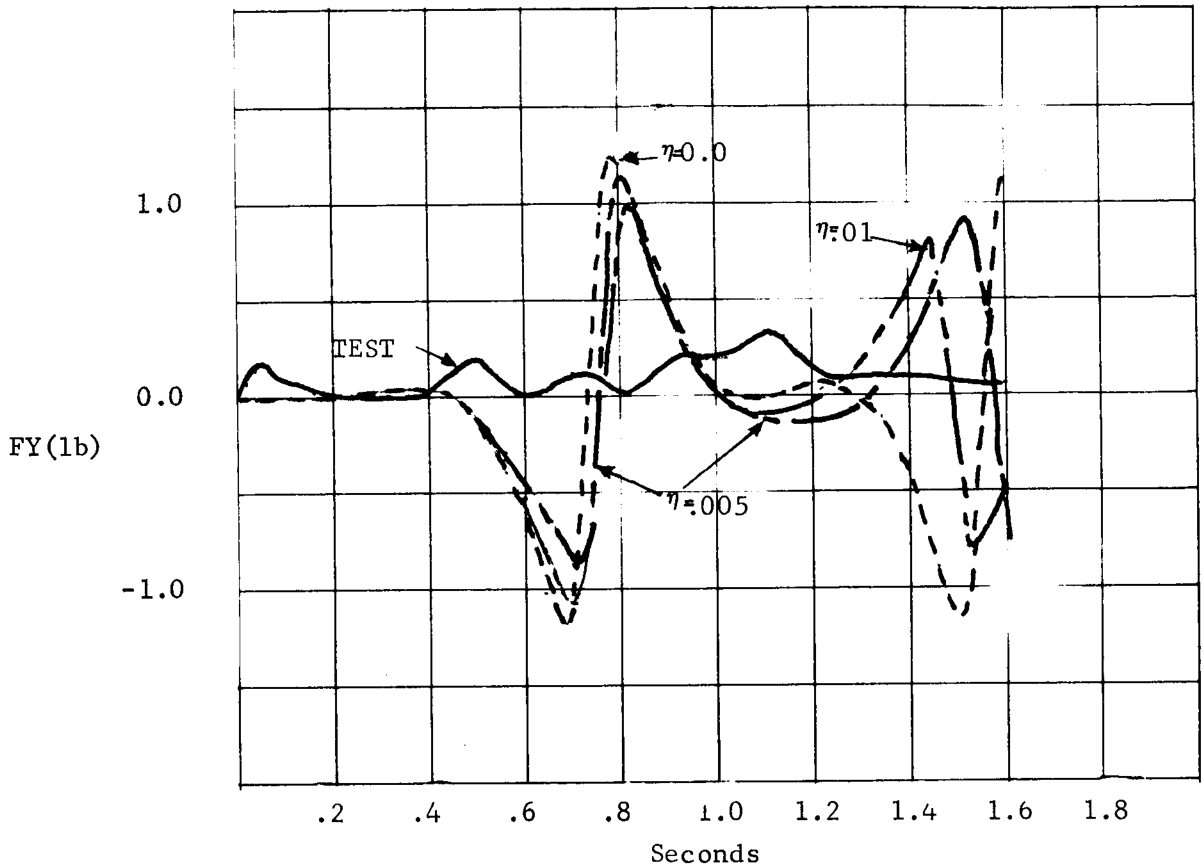


FIGURE IV-6. TEST 14, $\theta X = 0^{o}$, 50% FILL, A_a = .09g



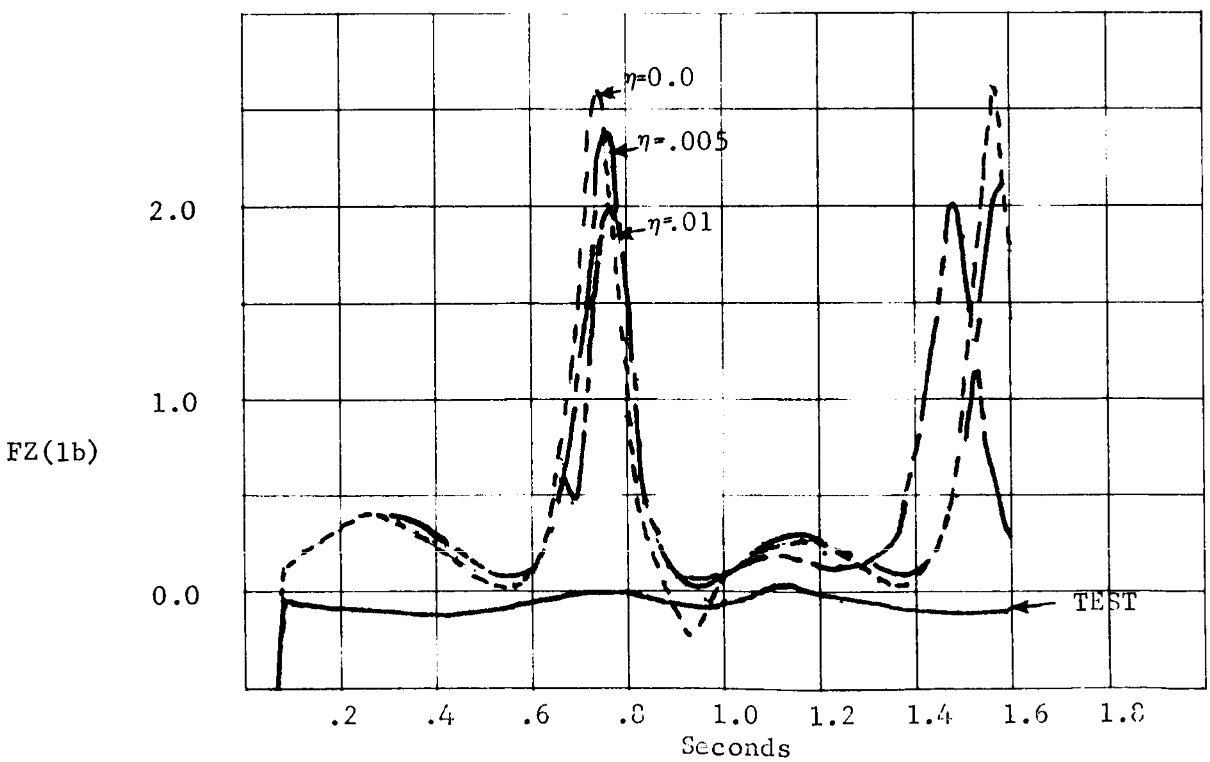
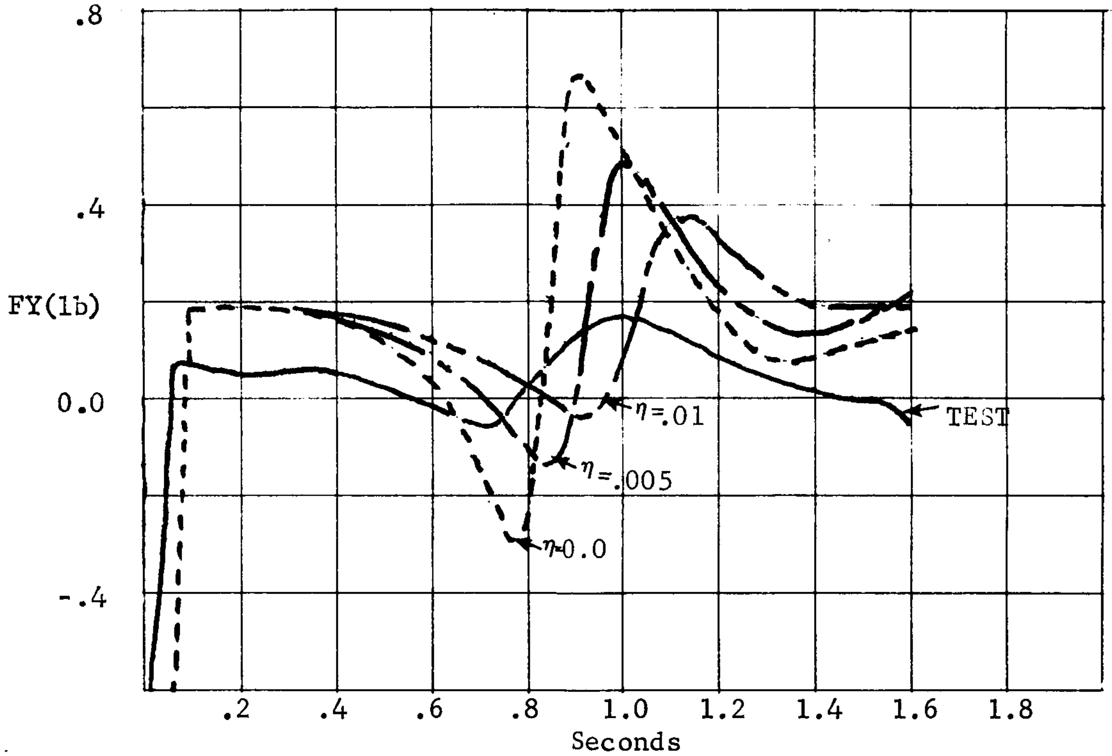


FIGURE IV-7. TEST 15, $\theta X = 0^o$, 75% FILL, $A_a = .09g$



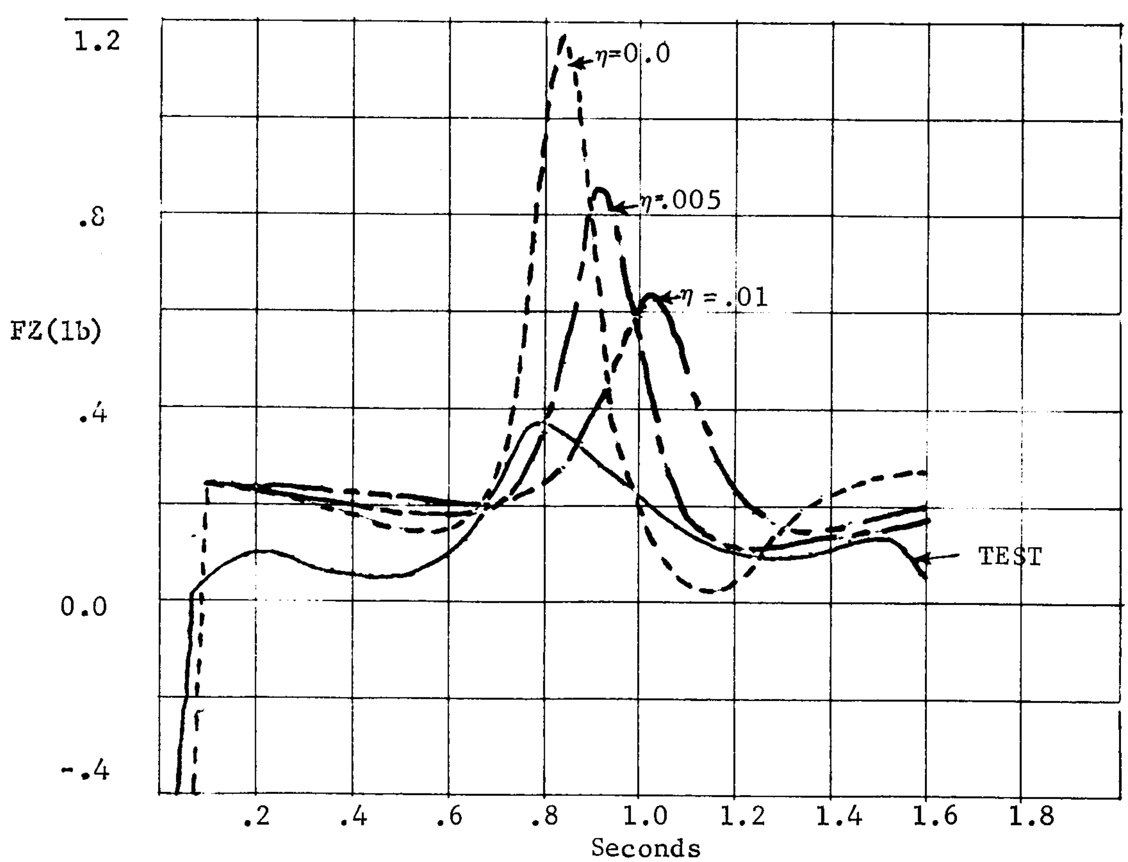


FIGURE IV-8. TEST 16, $\theta X = 45^{o}$, 25% FILL, A_a = .09g

V. CONCLUSIONS AND RECOMMENDATIONS

The concept, used in the analytical model, of a point mass moving on a constraint surface, yields results which compare favorably to measured test data for fill volumes up to 50%. Fine tuning of the analytical model may be achieved by better definition of the nature of viscous dissipative forces and allowing the fluid cm to move on trajectories interior to the constraint surface.

1. A study should be undertaken to determine the functional characteristics of the viscous dissipative force as related to fluid characteristics, fill volume and tank geometry.

2. The mechanical analog should be modified to allow the fluid cm to move interior to the constraint surface, dependent on internal fluid bond forces and applied acceleration fields.

The mechanical analog shows promise for use in the design of orbital control systems and the design of docking mechanisms.

3. The mechanical analog should be expanded to three dimensions and integrated into the general spacecraft equations for subsequent use in control system and loads analyses.

The test configuration is capable of providing insight to the character of liquid reorientation and the forces exerted on spacecraft by the moving liquid. Force definition is best for medium fill volumes and larger applied accelerations. Small, short term lateral accelerations are all that is required to produce liquid reorientation along the tank wall and to prevent the development of spout instabilities.

4. Further testing should be conducted to build the data bank necessary for analytical model verification. Testing should include various tank geometries; ogive, conical, etc. In addition, scale propellant management devices, baffels, etc., should be incorporated into the tests.

5. The possible application of the mechanical analog to reentry trajectory studies should be investigated for use on the shuttle external tank and other large reentry bodies which may contain significant amounts of propellant.

VI. REFERENCES

1. W. H. T. Loh (ed): "Jet, Rocket, Nuclear, Ion and Electric Propulsion: Theory and Design." Chapter 17, "Zero-g Propulsion Problems." Springer-Verlag, New York, 1968.

2. T. A. Coney: "Surface Tension, Viscosity and Density Measurements of Two Fluorocarbon Solvents, FC-43 and FC-78." NASA TM X-1862, Lewis Research Center, Cleveland, Ohio, August 1969.

3. H. N. Abramson: "The Dynamic Behavior of Liquids in Moving Containers." NASA SP-106, 1966.

4. R. L. Wohlen: "Synthesis of Dynamic Systems Using FORMA - Fortran Matrix Analysis." Martin Marietta Corporation, MCR-71-75, Volume IV, NAS8-25922, May 1971.

5. T. E. Bowman: "Cryogenic Liquid Experiments in Orbit; Vol. I, Liquid Settling and Interface Dynamics." Martin Marietta Corporation, Denver, Colorado, December 1966.

6. T. E. Bowman: "Response of the Free Surface of a Cylindrically Contained Liquid to Off-Axis Accelerations." Proceedings of the 1966 Heat Transfer and Fluid Mechanics Institute, Stanford University Press, 1966.

7. J. A. Salzman and W. J. Masica: "Experimental Investigation of Liquid Propellant Reorientation." NASA TND-3789. Lewis Research Center, Cleveland, Ohio, January 1967.

8. J. A. Salzman and W. J. Masica: "Low-Gravity Reorientation in a Scale-Model Centaur Liquid-Hydrogen Tank," NASA TN D-7168, Lewis Research Center, Cleveland, Ohio, February 1973.

APPENDIX A - EXTENSION OF THE EQUATIONS OF MOTION TO THE GENERAL SPACECRAFT SYSTEM

This appendix details an approach whereby the tank/liquid mechanical analog may be included in a spacecraft system of governing equations. These equations are cast into a state space framework that can be automated on a digital computer to provide the basis for both time and frequency domain analyses. The methodology is presented in the form of interconnected bodies that have certain constraints which restrict the motion between the bodies. The bodies could well be a spacecraft, tank and liquid mass combination. The ensuing discussion describes some of the salient points relating to both the general form of the equations and their constraints.

Governing Equations

This general form of the governing system of equations has successfully been employed by Martin Marietta personnel to simulate the dynamics of interconnected spinning elastic bodies. The detailed derivations have been given by Mr. C. S. Bodley and Mr. A. C. Park.*

A canonical first-order coupled set of equations of the form

$$\left\{\dot{y}\right\} = f\ (y,t) \qquad \text{(A-1)}$$

is employed in the mathematical simulation. The components of the state vector time derivatives will be further discussed for the spacecraft/tank/liquid combination. Particular attention will be devoted to the elemental makeup of the constituents.

The state equations that govern the coupled vehicle/tank/liquid motion may be depicted as describing the dynamical

* Carl S. Bodley and A. C. Park: Response of Flexible Space Vehicles to Docking Impact. MCR-70-2 (Vol. I), Martin Marietta Corporation, Denver, Colorado, March 1970.

motion of three bodies moving in inertial space. Constraint conditions are employed to both affix the tank to the vehicle and to define the liquid trajectory within the tank. These equations are stated in the following form.

$$
\begin{aligned}
\left\{ \dot{p} \right\} &= \left\{ G \right\} + \left[\Omega \right] \left\{ p \right\} + \left[b \right]^T \left\{ \lambda \right\} \\
\left\{ \dot{\beta} \right\} &= \left[B \right] \left\{ u \right\} \\
\left[b \right] \left\{ u \right\} &= \left\{ 0 \right\}
\end{aligned}
\tag{A-2}
$$

The state variables of the configuration space include ordinary momenta, $\{p\}$, position and attitude coordinates, $\{\beta\}$. The vector, $\{\beta\}$, contains such items as Euler angles and inertial position coordinates. The remaining items in the equations will receive additional attention throughout the discussion.

For a given body, k, of the system, the component ordinary momenta vector, $\{p\}_k$, is

$$
\left\{ p \right\}_k = \left[M \right]_k \left\{ u \right\}_k \tag{A-3}
$$

Further, there exists a transformation that relates the non-holonomic velocities, $\{u\}$, to generalized velocities.

$$
\left\{ u \right\}_k = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \\ u \\ v \\ w \end{bmatrix}_k = \left[\begin{array}{c:c} \pi_k & \\ \hdashline & \gamma_k \end{array} \right] \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} \tag{A-4}
$$

where in (A-4) the vector non-holonomic velocities $\{u\}$ contains the three projections $(\omega_x, \omega_y, \omega_z)_k$ of the angular velocity vector $\bar{\omega}_k$ onto the body fixed axis and the three projections of the reference point translational velocity $(u, v, w)_k$ onto the body axes. The elements of γ_k^{ij} $(i,j = 1,2,3)$ are direction cosines; the sub-matrix $\{\gamma\}$ $(i,j = 1,2,3)$ is an orthonormal rotation transformation relating the attitude of the body fixed axis system to the inertial frame. The sub-matrix, $\{\pi\}$, is also a rotation transformation; however, it is not orthonormal since it relates vector components based on an orthogonal basis to those of a skew basis; namely, the axes about which Euler rotations are measured.

The mass matrix for body k, appears as

$$\left[M\right]_k = \left[\begin{array}{c|c|c|c|c|c} J_{xx} & -J_{xy} & -J_{xz} & & -S_z & S_y \\ & J_{yy} & -J_{yz} & S_z & & -S_x \\ & & J_{zz} & -S_y & S_x & \\ \hline & S_z & -S_y & m & & \\ -S_z & & S_x & & m & \\ S_y & -S_x & & & & m \end{array}\right] = \left[\begin{array}{c|c} J & -S \\ \hline S & m \end{array}\right] \qquad \text{(A-5)}$$

The $\underline{kth}$ component of second part of the right hand side of $\underline{\text{(A-2)}}$, $\{\Omega\}_k \{p\}_k$, is further identified as

$$\left[\Omega\right]_k \left\{p\right\}_k = \left[\begin{array}{ccc|ccc} 0 & \omega_z & -\omega_y & & w & -v \\ -\omega_z & 0 & \omega_x & -w & & u \\ \omega_y & -\omega_x & 0 & v & -u & \\ \hline & & & 0 & \omega_z & -\omega_y \\ & & & \omega_z & 0 & \omega_x \\ & & & \omega_y & -\omega_x & 0 \end{array}\right] \left[\begin{array}{c} p(\omega_x) \\ p(\omega_y) \\ p(\omega_z) \\ p(u) \\ p(v) \\ p(w) \end{array}\right] \qquad \text{(A-6)}$$

The force/torque vector, $\{G\}_k$ contains the external forces and torques plus any stiffness and damping force that may arise through connections with the other bodies making up the system.

The constraint equations (third of A-2) are written in terms of the non-holonomic velocities, $\{u\}$. The coefficient $[b]$ are obtained from expressions of kinematic constraint and these same $[b]$ coefficients are transposed to premultiply the vector $\{\lambda\}$, providing constraint forces and torques.

Kinematic Coefficients

This subsection discusses the aforementioned kinematical relations involving expressions of relative and absolute velocities which lead to the form of the $[b]$ coefficients. The discussion will focus on two adjacent interconnected bodies.

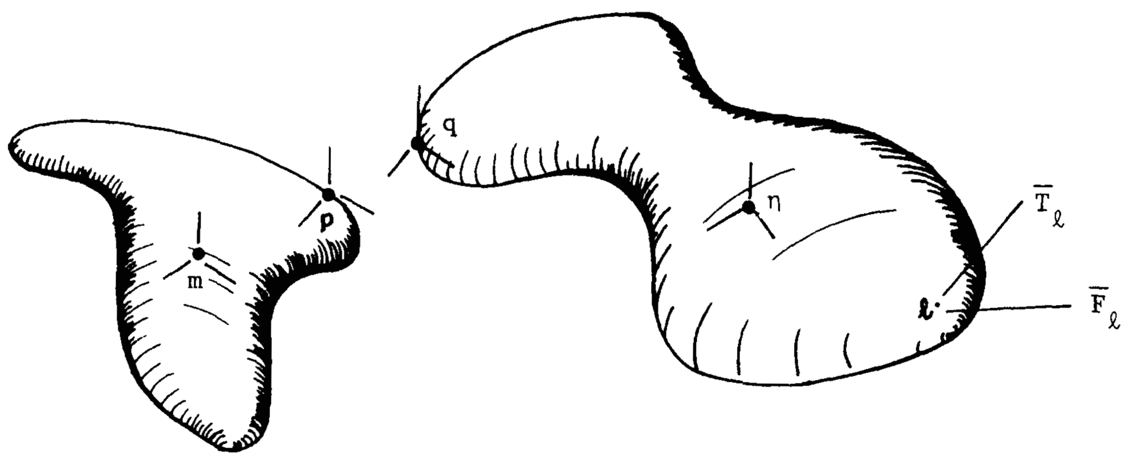


FIGURE A-1. TWO INTERCONNECTED BODY SYSTEM

The origins of the body reference systems are labeled m and n. The portions of the body where the bodies connect are located and labeled p and q.

In general, for each interconnected pair of bodies, there will be five (5) axis systems or coordinate bases. First, there will be an axis system fixed to each of the points, m, p, q, n (see Figure A-1). The fifth axis system is a skew or non-orthogonal basis comprising direction lines or unit vectors about which Euler rotations are measured. The Euler rotations are used to describe relative attitudes between the p and q frames.

At each connection joint, there will be six (6) components of relative velocity (three relative Euler angle rates and three relative translational rates that are measured along the skew axes) to be expressed

$$\begin{Bmatrix} \dot{\Delta}\theta \\ \hline \dot{\Delta} \end{Bmatrix} = \left[\begin{array}{c|c|c|c} -\pi^{-1}R^q_p R^p_m & & \pi^{-1}R^q_n & \\ \hline -R^p_m S_{mp} & -R^p_m & R^p_q R^q_n S_{nq} & R^p_q R^q_n \end{array}\right] \begin{Bmatrix} u_m \\ \hline u_n \end{Bmatrix} \qquad \text{(A-7)}$$

In (A-7) R^q_p is a (3x3) rotation transformation relating vector components in the p system to components in the q system. It transforms from p to q. The transformation R^p_m is similar, and note that the product ($R^q_p R^p_m = R^q_m$) transforms from m to q. The matrix, π^{-1}, relates vector components refered to orthogonal axes to those refered to skew axes. The matrix S_{mp} is a (3x3) skew symmetric matrix containing components of the vector positioning point p from m.

$$S_{mp} = \begin{bmatrix} 0 & z_p & -y_p \\ -z_p & 0 & x_p \\ y_p & -x_p & 0 \end{bmatrix} \qquad \text{(A-8)}$$

Finally, it is pointed out that certain rows from (A-7) constitute rows of $\{b\}$ and other rows of (A-7) are rows of matrix $\{B\}$.

APPENDIX B -- COMPUTER PROGRAM LISTING AND SAMPLE INPUT/OUTPUT

The following is a complete listing of program LAMPS and all associated non-FORMA subroutines. Immediately following the listing are sample input and output for Test 16. The output is normal and not the full checkout option. Following the sample printout are the plots generated for this test case.

```
      PROGRAM LAMPS(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1,FILMPL, LAS
     $TAPE2)                                                            LAS
C***********************************************************************LAS
C  LARGE AMPLITUDE SLOSH-- L A M P S --ANALYTIC SIMULATION              LAS
C  -      ---       -                                                   LAS
C                                                                       LAS
C     LAMPS IS A PROGRAM TO SIMULATE LARGE AMPLITUDE SLOSH OF PROPELLANT LAS
C     UNDER THE APPLICATION OF LOW G ACCELERATION FIELDS. THE SIMULATION LAS
C     IS 2-DIMENSIONAL. THE SIMULATION CONSTRAINS THE FLUID CENTER OF   LAS
C     MASS TO MOVE ON A SURFACE GENERATED BY SLOWLY ROTATING THE TANK   LAS
C     (ANALYTICALLY) IN 1 G AND TRACING THE PATH THE CENTER OF MASS     LAS
C     PRESCRIBES. IN THE SIMULATION THIS SURFACE IS REPRESENTED BY PIECE LAS
C     WISE CONTINUOUS ELLIPTICAL SEGMENTS. UPDATING OF THESE SEGMENTS IS LAS
C     PERFORMED TO INSURE THAT THE CENTER OF MASS DOES NOT DEVIATE      LAS
C     SUBSTANTIALLY FROM THE CONSTRAINT SURFACE. THE PROGRAM OUTPUTS    LAS
C     PARAMETERS WHICH TRACE THE FLUID CENTER OF MASS AS IT MOVES IN THE LAS
C     TANK IN ADDITION TO PRINTING TIME HISTORIES OF THE FORCES EXERTED LAS
C     BY THE FLUID ON THE TANK.                                         LAS
C***********************************************************************LAS
C     CODED BY RL BERRY FALL 1974  UNDER NAS8-30690                     LAS
C***********************************************************************LAS
C***********************************************************************LAS
C          M A R T I N   M A R I E T T A   A E R O S P A C E            LAS
C***********************************************************************LAS
C  INPUT FORMAT                                                         LAS
C  ------------                                                         LAS
C1000 READ(A6,I4,3A6) RUNNO,UNAME                                       LAS
C     IF(RUNNO.EQ.4HSTOP)STOP                                           LAS
C     READ(12A6)        TITLE1                                          LAS
C     READ(12A6)        TITLE2                                          LAS
C     READ(6E10.3)      XL,TR,TD,PCVOL,THETAX,FDEN                      LAS
C     READ(6I5)         NR,NTHET,NTABLE,IPRINT,NPRINT,NPLOT             LAS
C     READ(4E10.3)      VXX,CRIT,DELTAT,ENDT                            LAS
C     READ(4E10.3)      AYI,AZI,XMU,XNU,SMASS                           LAS
C     CALL COMENT       COMMENT CARDS, LAST CARD 10 ZEROS COLUMNS 1-10  LAS
C     IF(AZI.EQ.999..OR.AYI.EQ.999.)CALL READ(ACCEL,NA,NC,K1,3)         LAS
C     IF(NTABLE.LE.0)CALL READ(TABLE,NTABLE,NCT,K1,2)                   LAS
C     GO TO 1000                                                        LAS
C                                                                       LAS
C                                                                       LAS
C  DEFINITION OF INPUT VARIABLES                                        LAS
C  -----------------------------                                        LAS
C  RUNNO  = RUN NUMBER PRINTED IN PAGE HEADING.                         LAS
C  TITLE1 = TITLE CARD PRINTED IN PAGE HEADING.                         LAS
C  TITLE2 = TITLE CARD PRINTED IN PAGE HEADING.                         LAS
C  XL     = LENGTH OF PROPELLANT TANK CYLINDRICAL SECTION. (L UNITS)    LAS
C  TR     = TANK RADIUS. (L UNITS)                                      LAS
C  TD     = HEIGHT OF TANK DOME FROM TOP OF CYLINDRICAL SECTION. (L UNITS) LAS
C  PCVOL  = PERCENTAGE TANK FILL .LE. 100.                              LAS
C  THETAX = ANGLE TANK IS ROTATED ABOUT X-AXIS IN INERTIAL TRIAD. (DEGREES) LAS
C  FDEN   = PROPELLANT DENSITY. (F UNITS*SEC**2/L UNITS**4)             LAS
C  NR     = NUMBER OF RADIAL INTEGRATION INCREMENTS ON TANK RADIUS FOR  LAS
C           DETERMINING TANK CG. SUGGEST NR= 50.                        LAS
C  NTHET  = NUMBER OF ANGULAR INTEGRATION INCREMENTS AROUND TANK        LAS
C           CIRCUMFERENCE FOR DETERMINING TANK CG. SUGGEST NTHET= 50.   LAS
C  NTABLE = 0, READ IN A TABLE DESCRIBING CONSTRAINT SURFACE (PHI VS R). LAS
C         = N, LAMPS WILL DEFINE AN AXIS-SYMMETRIC CONSTRAINT SURFACE   LAS
C              TO BE STORED IN A TABLE AS PHI VS R WITH NTABLE VALUES   LAS
C              OF PHI FROM 0 TO 90 DEG. (N.GT.0.LE.20.)                 LAS
C  IPRINT = 1, NORMAL PRINTOUT.                                         LAS
C           2, FULL CHECKOUT PRINTOUT.                                  LAS
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
C  NPRINT = LAMPS WILL PRINT EVERY NPRINT(TH) TIME POINT.                 LAS
C  NPLOT  = 0, NO PLOTS WILL BE GENERATED.                                 LAS
C         = 1, GENERATE TIME HISTORY PLOTS OF VTDOT,VT,BETADOT,BETA,       LAS
C              FY,FZ,MX AND FLUID POSITION Y VS Z.                         LAS
C  VXX    = ITERATION CUTOFF (PERCENT FLUID VOLUME) FOR INITIAL CALCULAT-  LAS
C           ION OF FLUID CG, SUGGEST VXX= 2.0.                             LAS
C  CRIT   = UPDATE CRITERIA , PERCENTAGE DEVIATION FROM R(TABLE) ALLOWED.  LAS
C           IF /R(ACTUAL)-R(TABLE)/.GT.(CRIT*R(TABLE)/100.) UPDATE.        LAS
C  DELTAT = TIME INCREMENT FOR INTEGRATING THE EQUATIONS OF MOTION.(SEC)   LAS
C  ENDT   = TIME CUTOFF FOR PROGRAM TERMINATION. (SEC)                     LAS
C  AYI    = APPLIED Y ACCELERATION IN INERTIAL TRIAD.(L UNITS/SEC**2)      LAS
C           MUST NOT EQUAL 0.                                              LAS
C         = 999.,READ IN TIME HISTORY ACCELERATION TABLE.(ACCEL)           LAS
C  AZI    = APPLIED Z ACCELERATION IN INERTIAL TRIAD.(L UNITS/SEC**2)      LAS
C         = 999.,READ IN TIME HISTORY ACCELERATION TABLE.(ACCEL)           LAS
C  XMU    = COEF. WHICH RELATES FRICTION FORCE TO INERTIAL FORCE.(N.D.)    LAS
C  XNU    = COEF. WHICH RELATES FRICTION FORCE TO CENTER OF MASS           LAS
C           VELOCITY. (F UNITS*SEC/L UNITS)                                LAS
C  SMASS  = STRUCTURAL MASS ASSUMED INERT AT CENTER OF TANK TRIAD.         LAS
C           SMASS IS TANK STRUCTURE MASS AND IS USED IN CALCULATING        LAS
C           FORCES FOR COMPARISON WITH TEST DATA.(F UNITS*SEC**2/L UNITS)  LAS
C  ACCEL  = MATRIX OF ACCELERATION TIME HISTORIES READ IF EITHER AYI OR    LAS
C           AZI.EQ.999. OTHER VALUES OF EITHER AYI OR AZI WILL OVERRIDE    LAS
C           TABLE VALUES. MATRIX IS AN NA X 3 ,COLUMN 1 IS TIME (SEC),     LAS
C           COLUMN 2 IS AYI, COLUMN 3 IS AZI (L UNITS/SEC**2). NA.LE.20.   LAS
C           AYI MUST NOT EQUAL 0. AT TIME= 0.                              LAS
C  TABLE  = CONSTRAINT SURFACE TABLE  NTABLE X 2 . NTABLE DEFINED IN       LAS
C           CALL READ. COLUMN 1 IS CENTER OF MASS LOCATION PHI (DEGREES),  LAS
C           COLUMN 2 IS CORRESPONDING DISTANCE FROM TANK TRIAD ORIGIN      LAS
C           R (L UNITS). NTABLE.LE.20.                                     LAS
C                                                                          LAS
C                                                                          LAS
C                                                                          LAS
C  DEFINITION OF OUTPUT PARAMETERS                                         LAS
C  -------------------------------                                         LAS
C  TIME   = SIMULATION TIME. (SEC)                                         LAS
C  VTDOT  = FLUID CM ACCELERATION. (L UNITS/SEC**2)                        LAS
C  VT     = FLUID CM VELOCITY. (L UNITS/SEC)                               LAS
C  BETADOT= ANGULAR VELOCITY OF VELOCITY VECTOR. (DEGREES/SEC)             LAS
C  BETA   = ANGLE THE VELOCITY VECTOR MAKES WITH THE TANK TRIAD Y AXIS     LAS
C           (DEGREES.GE.0..LE.360.)                                        LAS
C  X,Y,Z  = FLUID CM LOCATION IN TANK TRIAD. (L UNITS)                     LAS
C  R      = RADIAL DISTANCE FROM TANK TRIAD ORIGIN TO FLUID CM. (L UNITS)  LAS
C  PHI    = FLUID CM LOCATION AS ANGLE MEASURED FROM TANK TRIAD Y AXIS     LAS
C           TO RADIAL VECTOR R. (DEGREES)                                  LAS
C  AY,AZ  = APPLIED ACCELERATIONS AYI AND AZI TRANSFORMED TO THE TANK      LAS
C           TRIAD. (L UNITS/SEC**2)                                        LAS
C  ACO,CCO= COEFS. IN ELLIPTICAL SURFACE EQUATION FOR THE ELLIPTICAL       LAS
C           SEGMENT REPRESENTING THE CONSTRAINT SURFACE. (N.D.)            LAS
C           ACO*Y**2+CCO*Z**= 1.0                                          LAS
C  RHO    = RADIUS OF GYRATION OF THE ELLIPTICAL SURFACE AT X,Y,Z.         LAS
C           (L UNITS)                                                      LAS
C  TANGENT= J AND K ARE COMPONENTS OF THE INSTANTANEOUS UNIT TANGENT       LAS
C           VECTOR WHICH IS THE DIRECTION OF THE VELOCITY VECTOR. (N.D.)   LAS
C  NORMAL = J AND K ARE COMPONENTS OF THE INSTANTANIANEOUS UNIT NORMAL     LAS
C           VECTOR TO THE ELLIPTICAL SEGMENT. (N.D.)                       LAS
C  FY,FZ  = FORCES EXERTED ON TANK SUPPORTS DUE TO FLUID MOTION AND TANK   LAS
C           STRUCT.  INERTIAL FORCES, IN TANK TRIAD. (F UNITS)             LAS
C  MX     = MOMENT EXERTED ON TANK SUPPORTS DUE TO FLUID MOTION, IN        LAS
C           TANK TRIAD. (L UNITS*F UNITS)                                  LAS
C  KEY1   = 0, MODEL FREE TO UPDATE ELLIPTICAL SURFACE AT WILL.            LAS
C           1, LAST UPDATE PERFORMED UNTIL BETA ENTERS A NEW QUADRANT.     LAS
```

```
C              FLUID CM IS OUTSIDE TANGENT TO CONSTRAINT SURFACE AT           LAS
C              AXIS INTERCEPT, HENCE NO UPDATE IS PERFORMED.                  LAS
C          = 2, LAST UPDATE PERFORMED UNTIL BETA ENTERS A NEW QUADRANT.       LAS
C              FLUID CM EXCEED CRIT CRITERIA AND IS WITHIN 20 DEGREES         LAS
C              OF AN AXIS INTERCEPT.                                          LAS
C          = 3, LAST UPDATE PERFORMED UNTIL BETA ENTERS A NEW QUADRANT.       LAS
C              FLUID CM EXCEEDS CRIT CRITERIA BUT IS WITHIN 1 DEG OF          LAS
C              AXIS INTERCEPT, HENCE NO UPDATE IS PERFORMED.                  LAS
C  KEY2    = 0, NO UPDATE WAS PERFORMED AT LAST TIME POINT.                   LAS
C          = 1, UPDATE WAS PERFORMED AT LAST TIME POINT.                      LAS
C  NQB     = QUADRANT OF THE ANGLE BETA.(1,2,3,4)                             LAS
C  NQF     = QUADRANT OF THE ANGLE PHI.(1,2,3,4)                              LAS
C                                                                             LAS
C                                                                             LAS
C NOTES                                                                       LAS
C -----                                                                       LAS
C  1) THE UNITS OF THE OUTPUT PARAMETERS ARE DEPENDANT ON THE UNITS OF        LAS
C     THE INPUT PARAMETERS. EITHER METRIC OR ENGLISH UNITS MAY BE USED.       LAS
C                                                                             LAS
C  2) L UNITS - LENGTH UNITS, IN,FT,METERS,CM, ETC.                           LAS
C     F UNITS - FORCE UNITS, LB,KG,GRAMS, ETC.                                LAS
C     ALL TIME UNITS ARE SECONDS.                                             LAS
C     ALL ANGLE UNITS ARE DEGREES.                                            LAS
C                                                                             LAS
C  3) ZZBOMB ERRORS-                                                          LAS
C      NERROR=1, SUBROUTINE FLUDCG FAILED TO CONVERGE.                        LAS
C             2, AYI= 0. AT TIME= 0.                                          LAS
C                                                                             LAS
C  4) SUBROUTINES CALLED BY LAMPS-- SURF,FLUDCG,ECOEF,ETAN,LOCATE,YDOT,       LAS
C      RKADAM,IQUAD,OUTPT,TLMPLT .                                            LAS
C     FORMA SUBROUTINES-- COMENT,INV5,PAGEHD,PLOT1,PLOTSS,READ,SMEQ1,         LAS
C      START,TERP1,TERP2,VCROSS,VDOT,WRITE,ZZBOMB .                           LAS
C                                                                             LAS
C                                                                             LAS
C*************************************************************************LAS
      COMMON/TANK/XL,TR,TD,PCVOL,FMASS,FDEN,VTANK,VFLUID                 LAS
      COMMON/STATE/BETAO,G,H,ENO(3),KEY1,KEY2                            LAS
      COMMON/VECTOR/V(2),VDT(2) ,FFRT,        A(3),RHO,QRK(2),PRK(4)     LAS
      COMMON/TIMESS/STARTT,DELTAT,ENDT,T,TMST                            LAS
      DIMENSION TABLE(20,2),ACCEL(20,3)                                  LAS
      DATA NIT,NOT/5,6/                                                  LAS
      CALL BPLT(2HNB,2HLC)                                               LAS
      K1= 20                                                             LAS
      NU1= 1                                                             LAS
      NU2=2                                                              LAS
  999 CALL START                                                         LAS
      REWIND NU1                                                         LAS
      REWIND NU2                                                         LAS
C*******************************************************************LAS
C  INPUT DATA SECTION                                                    LAS
C*******************************************************************LAS
C                                                                        LAS
      READ(NIT,1000)XL,TR,TD,PCVOL,THETAX,FDEN                           LAS
C*****READ CONTROL AND INTEGRATION PARAMETERS*************************LAS
      READ(NIT,1010)NR,NTHET,NTABLE,IPRINT,NPRINT,NPLOT                  LAS
      READ(NIT,1000)VXX,CRIT,DELTAT,ENDT                                 LAS
C*****READ APPLIED ACCELERATIONS AND FRICTION FORCE COEFS**************LAS
      READ(NIT,1000)VXX,CRIT,DELTAT,ENDT                                 LAS
      READ(NIT,1000)AYI,AZI,XMU,XNU,SMASS                                LAS
C                                                                        LAS
C*****PRINT INPUT DATA************************************************LAS
      CALL PAGEHD                                                        LAS
```

```
      WRITE(NOT,2000)
      WRITE(NOT,2010)XL,TR,TD,PCVOL,THETAX,FDEN,NR,NTHET,VXX,NTABLE,
     2IPRINT,NPRINT,NPLOT,SMASS,CRIT,DELTAT,ENDT,AYI,AZI,XMU,XNU
      CALL COMENT
      IF(AYI.EQ.999..OR.AZI.EQ.999.)CALL READ(ACCEL,NA,NC,K1,3)
C**********************************************************************
C   INITIALIZATION SECTION
C**********************************************************************
      IP= 2
      IF(IPRINT.GT.1)IP= 1
C   FIND FLUID CONSTRAINT SURFACE
      IF(NTABLE.GT.0)GOTO 5
      CALL READ(TABLE,NTABLE,NCT,K1,2)
      DO 6 I=1,NTABLE
      TABLE(I,1)=TABLE(I,1)*2.*3.141592654/360.
    6 CONTINUE
      GOTO 7
    5 CALL SURF(NR,NTHET,VXX,NTABLE,TABLE,K1,IP)
C   FIND INITIAL FLUID CG
    7 THETA=THETAX/57.2957795
      IF(THETAX.NE.999.)GO TO 10
      READ(NIT,1000)GY,GZ
      GX= 0.0
      GO TO 20
   10 GX= 0.0
      GY= SIN(THETA)
      GZ= COS(THETA)
   20 CALL FLUDCG(GX,GY,GZ,NR,NTHET,VXX,X,Y,Z,IE,1)
      WRITE(NOT,2020)
      IF(IE.NE.0)CALL ZZBOMB(5HLAMPS,1)
      X=0.0
C   FIND ELLIPTICAL SURFACE WHICH APPROXIMATES CONSTRAINT SURFACE
      CALL ECOEF(X,Y,Z,ACO,CCO,NTABLE,TABLE,K1,1,CRIT)
C   FIND APPLIED ACCEL. IN TANK TRIAD AT T= 0.
      T= 0.0
      KEY3= 0
      KEY4= 0
      IF(AYI.NE.999.)GO TO 30
      KEY3= 1
      CALL TERP1(ACCEL(1,1),T,ACCEL(1,2),AYI,NA,1,1,K1,1)
      IF(AYI.EQ.0.0)CALL ZZBOMB(5HLAMPS,2)
   30 IF(AZI.NE.999.)GO TO 40
      KEY4= 1
      CALL TERP1(ACCEL(1,1),T,ACCEL(1,3),AZI,NA,1,1,K1,1)
   40 A(1)= 0.0
      A(2)= AZI*SIN(THETA)+AYI*COS(THETA)
      A(3)= AZI*COS(THETA)-AYI*SIN(THETA)
      IF(ABS(Y).GT..001)GOTO 15
      IF(Y.GT.0.0.AND.AYI.GT.0.0)Y=-1.*Y
      IF(Y.LT.0.0.AND.AYI.LT.0.0)Y=-1.*Y
   15 IF(ABS(Z).GT..001)GOTO 16
      IF(Z.GT.0.0.AND.AYI.LT.0.0)Z=-1.*Z
      IF(Z.LT.0.0.AND.AYI.GT.0.0)Z=-1.*Z
   16 CONTINUE
C   DEFINE DIRECTION OF FLUID CG VELOCITY VECTOR
       VT=0.0
      CALL ETAN(ACO,CCO,Y,Z,A(2),A(3),G,H,VT)
C*****PRINT TANK AND FLUID VOLUMES AND FLUID MASS***********************
      CALL PAGEHD
      WRITE(NOT,2030)VTANK,VFLUID,FMASS
C
C   INITIAL CONDITIONS
```

```
      BETA= ATAN2(H,G)
      IF(BETA.LT.0.0)BETA=2.*3.141592654+BETA
      BETAO= BETA
      R= (Y**2+Z**2)**0.5
      IF(ABS(Y).GT.1.E-20)GO TO 45
      IF(Z.GE.0.)PHI= 3.141592654/2.
      IF(Z.LT.0.)PHI= -3.141592654/2.
      GO TO 46
   45 PHI= ATAN2(Z,Y)
   46 IF(PHI.LT.0.0)PHI= 2.*3.141592654+PHI
      ENOM= ((ACO*Y)**2+(CCO*Z)**2)**0.5
      ENO(1)= 0.0
      ENO(2)= ACO*Y/ENOM
      ENO(3)= CCO*Z/ENOM
      PHD=   PHI*57.2957795
      IF(PHD.GT.315..OR.PHD.LT.45.)GO TO 47
      IF(PHD.GT.135..AND.PHD.LT.225.)GO TO 47
      W= Y
      CXX= ACO
      AXX= CCO
      GO TO 48
   47 W= Z
      CXX= CCO
      AXX= ACO
   48 DY= (-1.*CXX*W)/(AXX*((1.-CXX*W**2)/AXX)**0.5)
      DY2=((-1.*CXX)/(AXX*((1.-CXX*W**2)/AXX)**0.5))-((CXX*W)**2/
     1(AXX**2*((1.-CXX*W**2)/AXX)**1.5))
      IF(ABS(DY2).GT.1.E-21)GO TO 41
      RHO= 1.E+21
      GO TO 42
   41 RHO= ABS((1.+DY**2)**1.5/DY2)
   42 CALL VDOT(ENO,A,ENOA,DUM,DUM,DUM)
      FINR= -1.*FMASS*(ENOA-(VT**2/RHO))
      FFRT= XMU*ABS(FINR)+XNU*ABS(VT)
      FINR= -1.*FMASS*(ENOA-(VT**2/RHO))
      V(1)= VT
      V(2)= BETA
      CALL YDOT
      KEY1= 0
      KEY2= 0
      FZ=FFRT*H+FINR*ENO(3)-A(3)*SMASS
      FY=FFRT*G+FINR*ENO(2)-A(2)*SMASS
      FMX=(FFRT*H+FINR*ENO(3))*Y-(FFRT*G+FINR*ENO(2))*Z
      NQB= IQUAD(BETA)
      IF(Y.GT.0..AND.Z.GE.0.) NQF=1
      IF(Y.LE.0..AND.Z.GT.0.) NQF=2
      IF(Y.LT.0..AND.Z.LE.0.) NQF=3
      IF(Y.GE.0..AND.Z.LT.0.) NQF=4
      BETD= BETA*57.2957795
      BETDD=VDT(2)*57.2957795
      WRITE(NU1)T, VDT(1),VT,  BETDD,BETD,X,Y,Z,R,PHD,A(2),A(3),ACO,CCO,
     2           RHO,G,H,ENO(2),ENO(3),FY,FZ,FMX,KEY1,KEY2,NQB,NQF
      IF(IPRINT.NE.2)GOTO 49
      CALL PAGEHD
      WRITE(NOT,7001)
      WRITE(NOT,7000)T,VDT(1),VT, BETDD,BETD,X,Y,Z,R,PHD,A(2),A(3),ACO,
     *CCO,RHO,G,H,ENO(2),ENO(3),FY,FZ,FMX,KEY1,KEY2,NQB,NQF,FINR,FFRT
   49 WRITE(NU2)T,VDT(1),VT,BETDD,BETD,PHD,Y,Z,FY,FZ,FMX
      NKT=1
C     SET UP PARAMETERS FOR INTEGRATION ROUTINE--RKADAM
      NT= 0
      STARTT= 0.0
```

```
C**************************************************************************
C  INTEGRATION LOOP--SOLUTION OF EQUATIONS OF MOTION
C**************************************************************************
  333 CALL RKADAM(2,NT)
      NKT=NKT+1
C  LOCATE FLUID CG IN TANK TRIAD--Y,Z
      G=COS(V(2))
      H=SIN(V(2))
      CALL LOCATE(ACO,CCO,V(2),Y,Z)
C  CALCULATE REQD OUTPUT PARAMETERS
      VT= V(1)
      BETA= V(2)
      IF(BETA.LT.0.0)BETA= 2.*3.141592654+BETA
      R= (Y**2+Z**2)**0.5
      PHI= ATAN2(Z,Y)
      IF(PHI.LT.0.0)PHI= 2.*3.141592654+PHI
      ENOM= ((ACO*Y)**2+(CCO*Z)**2)**0.5
      ENO(2)= ACO*Y/ENOM
      ENO(3)= CCO*Z/ENOM
      PHD=   PHI*57.2957795
      IF(PHD.GT.315..OR.PHD.LT.45.)GO TO 60
      IF(PHD.GT.135..AND.PHD.LT.225.)GO TO 60
      W= Y
      CXX= ACO
      AXX= CCO
      GO TO 61
   60 W= Z
      CXX= CCO
      AXX= ACO
   61 DY= (-1.*CXX*W)/(AXX*((1.-CXX*W**2)/AXX)**0.5)
      DY2=((-1.*CXX)/(AXX*((1.-CXX*W**2)/AXX)**0.5))-((CXX*W)**2/
     1(AXX**2*((1.-CXX*W**2)/AXX)**1.5))
      IF(ABS(DY2).GT.1.E-21)GO TO 62
      RHO= 1.E+21
      GO TO 63
   62 RHO= ABS((1.+DY**2)**1.5/DY2)
   63 IF(KEY3.EQ.1)CALL TERP1(ACCEL(1,1),T,ACCEL(1,2),AYI,NA,1,1,K1,1)
      IF(KEY4.EQ.1)CALL TERP1(ACCEL(1,1),T,ACCEL(1,3),AZI,NA,1,1,K1,1)
      A(2)= AZI*SIN(THETA)+AYI*COS(THETA)
      A(3)= AZI*COS(THETA)-AYI*SIN(THETA)
      CALL VDOT(ENO,A,ENOA,DUM,DUM,DUM)
      FINR= -1.*FMASS*(ENOA-(VT**2/RHO))
      FFRT= XMU*ABS(FINR)+XNU*ABS(VT)
      FZ=FFRT*H+FINR*ENO(3)-A(3)*SMASS
      FY=FFRT*G+FINR*ENO(2)-A(2)*SMASS
      FMX=(FFRT*H+FINR*ENO(3))*Y-(FFRT*G+FINR*ENO(2))*Z
      NQB= IQUAD(BETA)
      IF(Y.GT.0..AND.Z.GE.0.)NQF= 1
      IF(Y.LE.0..AND.Z.GT.0.)NQF= 2
      IF(Y.LE.0..AND.Z.LE.0.)NQF= 3
      IF(Y.GE.0..AND.Z.LT.0.)NQF= 4
C  STORE DATA ON NU1 FOR OUTPUT
      BETD= BETA*57.2957795
      BETDD=VDT(2)*57.2957795
      WRITE(NU1)T,VDT(1),VT, BETDD,BETD,X,Y,Z,R,PHD,A(2),A(3),ACO,CCO,
     2          RHO,G,H,ENO(2),ENO(3),FY,FZ,FMX,KEY1,KEY2,NQB,NQF
      IF(IPRINT.NE.2)GOTO 51
      WRITE(NOT,7000)T,VDT(1),VT, BETDD,BETD,X,Y,Z,R,PHD,A(2),A(3),ACO,
     *CCO,RHO,G,H,ENO(2),ENO(3),FY,FZ,FMX,KEY1,KEY2,NQB,NQF,FINR,FFRT
   51 WRITE(NU2)T,VDT(1),VT,BETDD,BETD,PHD,Y,Z,FY,FZ,FMX
      KEY2=0
      IF(T.GE.ENDT)GO TO 555
```

```
C   CHECK TO SEE IF ELLIPSE NEEDS UPDATING
        IF(VT.LE.0.0)GOTO 70
        IF(KEY1.EQ.0)GO TO 50
        NQO= IQUAD(BETAO)
        NQN= IQUAD(BETA)
        IF(NQO.EQ.NQN) BETAO=BETA
        IF(NQO.EQ.NQN)GO TO 333
   50 KEY1= 0
        CALL ECOEF(X,Y,Z,ACO,CCO,NTABLE,TABLE,K1,2,CRIT)
C   IF KEY2= 1 ELLIPSE UPDATED IF NOT RETURN AND INTEGRATE
        BETAO= BETA
        IF(KEY2.NE.1)GO TO 333
        CALL ETAN(ACO,CCO,Y,Z,A(2),A(3),G,H,VT)
   70 IF(VT.GT.0.0)GOTO 75
        VT=0.0
        G=-1.*G
        H=-1.*H
        KEY1=0
   75 BETA= ATAN2(H,G)
        IF(BETA.LT.0.0)BETA= 2.*3.141592654+BETA
        BETAO=BETA
        V(1)=VT
        V(2)= BETA
        IF(PHD.GT.315..OR.PHD.LT.45.)GO TO 65
        IF(PHD.GT.135..AND.PHD.LT.225.)GO TO 65
        W= Y
        CXX= ACO
        AXX= CCO
        GO TO 66
   65 W= Z
        CXX= CCO
        AXX= ACO
   66 DY= (-1.*CXX*W)/(AXX*((1.-CXX*W**2)/AXX)**0.5)
        DY2=((-1.*CXX)/(AXX*((1.-CXX*W**2)/AXX)**0.5))-((CXX*W)**2/
     1(AXX**2*((1.-CXX*W**2)/AXX)**1.5))
        IF(ABS(DY2).GT.1.E-21)GO TO 67
        RHO= 1.E+21
        GO TO 68
   67 RHO= ABS((1.+DY**2)**1.5/DY2)
   68 ENOM=((ACO*Y)**2+(CCO*Z)**2)**0.5
        ENO(2)= ACO*Y/ENOM
        ENO(3)= CCO*Z/ENOM
C       IF(IPRINT .NE.2)GOTO 333
        WRITE (NOT,7002)T
        WRITE(NOT,7000)BETA,G,H,ENO(2),ENO(3),RHO,VT
        GO TO 333
C***********************************************************************
C   OUTPUT SECTION
C***********************************************************************
  555 CALL OUTPT(NU1,NPRINT,ENDT)
        IF(NPLOT.GT.0)CALL TLMPLT(NKT,NU2,TR)
        GO TO 999
C***********************************************************************
C   FORMAT STATEMENTS
C***********************************************************************
 1000 FORMAT(6E10.3)
 1010 FORMAT(6I5)
 2000 FORMAT(///,21X,61HLARGE AMPLITUDE SLOSH --  L A M P S  -- ANALYTIC
     1AL SIMULATION,/,21X,1H-,5X,3H---,7X,1H-,///,41X,19HI N P U T   D A
     2 T A,/,41X,19H*******************)
 2010 FORMAT(//,41X,3HXL=,2X,F8.2,/,41X,3HTR=,2X,F8.2,/,41X,3HTD=,2X,F8.
     12,/,38X,6HPCVOL=,3X,F7.2,/,37X,7HTHETAX=,4X,F6.2,/,39X,5HFDEN=,5X,
```

```
     2E9.2,/,41X,3HNR=,2X,I5,/,38X,6HNTHET=,2X,I5,/,40X,4HVXX=,4X,F6.2,/LAS 1840
     3,37X,7HNTABLE=,2X,I5,/,37X,7HIPRINT=,2X,I5,/,37X,7HNPRINT=,2X,I5,/LAS 1850
     4,38X,7HNPLOT= ,1X,I5,/,38X,7HSMASS= ,4X,E11.4,/                  LAS 1855
     5,39X,5HCRIT=,4X,F6.2,/,37X,7HDELTAT=,3X,F8.3,/,39X,5HENDT=,2X,F9.3LAS 1860
     6,/,40X,4HAYI=,2X,F10.4,/,40X,4HAZI=,2X,F10.4,/,40X,5HXMU= ,4X,   LAS 1870
     7E11.4,/,40X,5HXNU= ,4X,E11.4)                                    LAS 1880
2020 FORMAT(//,17X,31H***INITIAL FLUID CG LOCATION***)                 LAS 1890
2030 FORMAT(/////,17X,30HTANK AND FLUID CHARACTERISTICS,/,17X,15(2H--),LAS 1900
     1/,17X,14HTANK VOLUME=  ,F11.4,2X,8HCU UNITS,//,16X,15HFLUID VOLUMELAS 1910
     2=  ,F11.4,2X,8HCU UNITS,//,18X,13HFLUID MASS=  ,F11.4,2X,17HF -SECLAS 1920
     3**2/L**4   )                                                     LAS 1930
7000 FORMAT(5X,12E10.3,/,5X,10E10.3,4I5,/,5X,2E10.3)                   LAS 1931
7001 FORMAT(//,20X,23HFULL CHECKOUT PRINT OUT,//,5X,19HORDER OF PRINT OLAS 1932
     2UT ,50HT,VTDOT,VT,BETADOT,BETA,X,Y,Z,R,PHI,A(2),A(3),ACO,,62HCCO,RLAS 1933
     3HO,G,H,ENO(2),ENO(3),FY,FZ,MX,KEY1,KEY2,NQB,NQF,FTNR,FFRT,//)    LAS 1934
7002 FORMAT(//,5X,23HUPDATE PERFORMED AT T= ,F9.3,/,5X,45HNEW VALUES BELAS 1935
     1TA(RAD),G,H,ENO(2),ENO(3),RHO,VT)                                LAS 1936
      END                                                              LAS 194*
```

```
      SUBROUTINE RKADAM(NEQ,NT)
C
      COMMON /TIMESS/ STARTT,DELTAT,ENDT,T,TMST
      COMMON/VECTOR/Y(2),YDT(2),FFRT,       A(3),RHO,QRK(2),PRK(4)
      COMMON/TANK/AL,TR,TD,PCVOL,FMASS,FDEN,VTANK,VFLUID
C
C*********************************************************************
C     RUNGE KUTTA (GILL MOD.) INTEGRATION ROUTINE
C     CODED BY CARL BODLEY , MARTIN MARIETTA CORP.
C     NEQ= NUMBER OF EQUATIONS
C     NT= NUMBER OF DELTAT STEPS COUNTER
C         INITIALLY MUST BE SET 0 IN CALLING PROGRAM
C*********************************************************************
      DATA EPS1, EPS2  /  1.E-8,  1.E-2   /
C
      IF (NT .GT. 0) GO TO 10
      QRK(1)= 0.
      QRK(2)= 0.
      PRK(1)= 0.5
      PRK(2)= 1.-SQRT(0.5)
      PRK(2)= 1.+SQRT(0.5)
      PRK(4)= 0.5
      TMST= 0.0
   10 DO 120 J = 1,4
      JIL = J
      DO 110 I=1,NEQ
      Z = YDT(I)*DELTAT
      GO TO (103,101,101,105), JIL
  101 R = PRK(JIL)*(Z - QRK(I))
      GO TO 107
  103 R = PRK(JIL)*Z - QRK(I)
      GO TO 107
  105 R = (Z - 2.*QRK(I))/6.
  107 Y(I) = Y(I) + R
  110 QRK(I) = QRK(I) + 3.*R - PRK(JIL)*Z
      IF (JIL .EQ. 1 .OR. JIL .EQ. 3) T = T + DELTAT/2.
  120 CALL YDOT
C
C
  300 NT = NT + 1
      ANT = NT
      TMST = ANT*DELTAT
      T = STARTT + TMST
C
      RETURN
      END
```

```
      SUBROUTINE ETAN(AAO,CCO,Y,Z,A,B,G,H,VT)
C*****************************************************************************
C  ETAN CALCULATES THE UNIT TANGENT VECTOR TO AN ELLIPTICAL SURFACE.
C              ETAN= GJ+HK ,    J= UNIT VECTOR Y DIRECTION.
C                               K= UNIT VECTOR Z DIRECTION.
C*****************************************************************************
C     CODED BY RL BERRY   SEPT 1974  UNDER NAS8-30690
C*****************************************************************************
C*****************************************************************************
C          M A R T I N   M A R I E T T A   A E R O S P A C E
C*****************************************************************************
C**   SUBROUTINE ARGUMENTS
C     --------------------
C      AAO= ELLIPTICAL SURFACE COEF. (Y)
C      CCO= ELLIPTICAL SURFACE COEF. (Z)
C      Y,Z= CURRENT FLUID CG LOCATION.
C      A,B= APPLIED ACCELERATION VECTOR COMPONENTS,TANK TRIAD.
C           ACC=AJ+BK
C      G,H= OUTPUT COMPONENTS OF ETAN.
C*****************************************************************************
      XG=-1.
      XH=-1.
      IF(G.GE.0.)XG=1.
       IF(H.GE.0.)XH=1.
      IF(ABS(Y).GT.0.0001)GO TO 10
      HH=0.0
      GG=1.0
      GO TO 20
   10 HH=(1./(((CCO*Z)/(AAO*Y))**2.+1.0))**0.5
      GG=(1.-HH**2)**0.5
   20 IF(VT.GT.0.0)GO TO 60
      VT= 0.0
      AA= -1.*A
      BB= -1.*B
      ACK1= AAO*Y
      ACK2= CCO*Z
      IF(ACK1.GE.0..AND.ACK2.GE.0.)GO TO 30
      IF(ACK1.LE.0..AND.ACK2.LE.0.)GO TO 30
      GO TO 40
   30 GG=-1.*GG
   40 ACK3= GG*AA+HH*BB
C IF FORCE IS PERPENDICULAR TO ETAN USE OLD ETAN FOR NEXT DELTA T.
      IF(ACK3.EQ.0.0)RETURN
      IF(ACK3.LT.0.0)GO TO 50
      G= GG
      H= HH
      RETURN
   50 G= -1.*GG
      H= -1.*HH
      RETURN
   60 G=XG*GG
       H=XH*HH
      RETURN
      END
```

```
      SUBROUTINE LOCATE(AA0,CC0,BETA,Y,Z)
      COMMON/STATE/BETAO,G,H,ENO(3),KEY1,KEY2
C*********************************************************************
C  LOCATE CALCULATES THE POSITION OF THE FLUID CG GIVEN BETA FROM
C  KNOWING-     1) SURFACE EQUATION
C               2)(ETAN)DOT(NORMAL)= 0
C*********************************************************************
C     CODED BY RL BERRY  SEPT 1974  UNDER NAS8-30690
C*********************************************************************
C*********************************************************************
C          M A R T I N   M A R I E T T A   A E R O S P A C E
C*********************************************************************
C**   SUBROUTINE ARGUMENTS
C     ------------------
C      AAO= ELLIPTICAL SURFACE COEF. (Y)
C      CCO= ELLIPTICAL SURFACE COEF. (Z)
C     BETA= STATE VARIABLE- ANGLE OF ETAN WITH HORIZONTAL.
C           (0 TO 2*PI RADIANS)
C      Y,Z= OUTPUT FLUID CG LOCATION, TANK TRIAD,-INPUT OLD LOCATION
C**
CZZBOMB-NERROR= 1, NQO=0 OR GT 4
C******CALLS SUBROUTINE ZZBOMB, FUNCTION IQUAD
C*********************************************************************
      Z0=1.0
      Y0=1.0
      IF(Y.LT.0.)Y0=-1.0
      IF(Z.LT.0.)Z0=-1.0
      ZN=((AAO*G**2)/((CCO*H)**2+AAO*CCO*G**2))**0.5
    5 YN= ((1.0-CCO*ZN**2)/AAO)**0.5
      NQO= IQUAD(BETAO)
      NQN= IQUAD(BETA)
      NDQ= NQN-NQO
      IF(NDQ.EQ.0)GO TO 10
      IF(NQO.EQ.1.AND.NQN.EQ.4)GOTO 20
      IF(NQO.EQ.1.AND.NQN.EQ.2)GOTO 30
      IF(NQO.EQ.1.AND.NQN.EQ.3)GOTO 10
      IF(NQO.EQ.2.AND.NQN.EQ.1)GOTO 30
      IF(NQO.EQ.2.AND.NQN.EQ.3)GOTO 20
      IF(NQO.EQ.2.AND.NQN.EQ.4)GOTO 10
      IF(NQO.EQ.3.AND.NQN.EQ.4)GOTO 30
      IF(NQO.EQ.3.AND.NQN.EQ.2)GOTO 20
      IF(NQO.EQ.3.AND.NQN.EQ.1)GOTO 10
      IF(NQO.EQ.4.AND.NQN.EQ.1)GOTO 20
      IF(NQO.EQ.4.AND.NQN.EQ.3)GOTO 30
      IF(NQO.EQ.4.AND.NQN.EQ.2)GOTO 10
      CALL ZZBOMB(6HLOCATE,1)
   10 AZ= 1.0*Z0
      AY= 1.0*Y0
      GO TO 60
   20 AZ= 1.0*Z0
      AY= -1.0*Y0
      GO TO 60
   30 AZ= -1.0*Z0
      AY= 1.0*Y0
   60 Y= AY*YN
      Z= AZ*ZN
      RETURN
      END
```

```
      FUNCTION IQUAD(BETA)
C*************************************************************************
C  IQUAD DETERMINES THE QUADRANT IN WHICH BETA (0 TO 2*PI RADIANS)
C  LIES
C*************************************************************************
C     CODED BY RL BERRY SEPT 1974 UNDER NAS8-30690
C            M A R T I N   M A R I E T T A   A E R O S P A C E
C*************************************************************************
      BD= BETA*57.29577951
      IF(BD.LT.0..AND.BD.LT.-360.)GO TO 10
      IF(BD.GT.0..AND.BD.GT.360.)GO TO 10
      GO TO 20
   10 N2PI= BD/360.
      BD= BD-(N2PI*360.)
   20 IF(BD.LT.0.)BD= 360.+BD
      IF(BD.EQ.360.)IQUAD= 1
      IF(BD.GE.0.0.AND.BD.LT.90.0)IQUAD= 1
      IF(BD.GE.90.0.AND.BD.LT.180.0)IQUAD= 2
      IF(BD.GE.180.0.AND.BD.LT.270.0)IQUAD= 3
      IF(BD.GE.270.0.AND.BD.LT.360.0)IQUAD= 4
      RETURN
      END
```

```
      SUBROUTINE ECOEF(XB,YB,ZB,ACO,CCO,NTABLE,TABLE,KR,IMODE,CRIT)      ECO   10
      COMMON/STATE/BETAO,G,H,ENO(3),KEY1,KEY2                            ECO   15
      COMMON/VECTOR/Y(2),YDT(2),FFRT,      A(3),RHO,QRK(2),PRK(4)        ECO   16
      DIMENSION TABLE(KR,1),YZ(2,2),YZI(2,2)                             ECO   20
C************************************************************************ECO** 10
C  ECOEF DETERMINES THE ELLIPTICAL SURFACE COEFFICIENTS ACO AND CCO      ECO** 20
C  WHICH BEST DEFINE THE SURFACE OF ALLOWABLE FLUID CG LOCATIONS IN      ECO** 30
C  THE REGION OF THE CURRENT FLUID CG LOCATION- XB,YB,ZB (IMODE=1).ECOEFECO** 40
C  USES THE SURFACE TABLE GENERATED IN SUBROUTINE SURF.  WILL ALSO       ECO** 50
C  CHECK FLUID CG TO SEE IF SUFFICIENT DEVIATION FROM THE SURFACE        ECO** 60
C  HAS OCCURED FOR ELLIPSOIDAL COEF. UPDATE TO TAKE PLACE PRIOR TO PER-  ECO** 70
C  FORMING UPDATE (IMODE=2).                                             ECO** 80
C**UPDATE CRITERIA- 1) R(ACTUAL).GT.(CRIT*R(TABLE)/100)                  ECO** 81
C  ---------------- 2) CG WITHIN 10 PERCENT*R(TANGENT) OF TANGENT        ECO** 82
C                   3) R(ACTUAL).GT.R(TANGENT)                           ECO** 83
C  IF R(ACTUAL).GE.R(TANGENT) UPDATE PERFORMED WITH MIRROR IMAGE OF      ECO** 84
C  CURRENT CG LOCATION. IF PHI WITHIN 20 DEG OF TANGENT AXIS INTERCEPT   ECO** 85
C  OR WITHIN 10 PERCENT INSIDE TANGENT, AXIS INTERCEPT POINT IS USED     ECO** 86
C  FOR UPDATE.                                                           ECO** 87
C                                                                        ECO** 88
C                                                                        ECO** 90
C  KEYS SET BY SUBROUTINE- KEY1= N, FINAL UPDATE UNTIL FLUID BETA        ECO** 91
C                                   ENTERS NEW QUADRANT                  ECO** 92
C                               = 0, UPDATE SHOULD CONTINUE AS REQD.     ECO** 93
C                           KEY2= 1, SURFACE UPDATE WAS PERFORMED.       ECO** 94
C                               = 0, NO SURFACE UPDATE WAS PERFORMED.    ECO** 95
C                                                                        ECO** 96
C    ELLIPTICAL SURFACE-  ACO*X**2+ACO*Y**2+CCO*Z**2 = 1                 ECO**100
C************************************************************************ECO**110
C     CODED BY RL BERRY   MAY 1974  UNDER NAS8-30690                     ECO**120
C************************************************************************ECO**130
C************************************************************************ECO**135
C           M A R T I N   M A R I E T T A   A E R O S P A C E            ECO**136
C************************************************************************ECO**137
C**   SUBROUTINE ARGUMENTS                                               ECO**140
C     --------------------                                               ECO**150
C XB,YB,ZB= CURRENT FLUID CG LOCATION.                                   ECO**160
C      ACO= OUTPUT ELLIPTICAL SURFACE COEF.                              ECO**170
C      CCO= OUTPUT ELLIPTICAL SURFACE COEF.                              ECO**180
C   NTABLE= NUMBER OF VALUES IN MATRIX TABLE.                            ECO**190
C    TABLE= MATRIX OF SURFACE LOCATIONS (/PHI/,R), SIZE(NTABLE,2).       ECO**200
C       KR= ROW DIMENSION OF TABLE IN CALLING PROGRAM-.GE.NTABLE.        ECO**210
C     DDEG= INCREMENT TO PHI FOR TABLE LOOKUP-.LE. 45 DEGREES.           ECO**220
C    IMODE= 1,DETERMINE ACO,CCO.                                         ECO**230
C           2,COMPARE CURRENT FLUID CG AGAINST ALLOWABLE SURF. IF OFF    ECO**240
C             BY CRIT UPDATE ACO,CCO...IF NOT RETURN TO CALLING PROGRAM.ECO**250
C     CRIT= PERCENTAGE DEVIATION FROM R(TABLE) ALLOWED,                  ECO**260
C           IF R(ACTUAL).GT.(CRIT*R(TABLE)/100) UPDATE ACO,CCO.          ECO**270
C**                                                                      ECO**280
C ZZBOMB...NERROR= 1, KR.LT.NTABLE                                       ECO**290
C*****CALLS SUBROUTINES TERP2,INV5,ZZBOMB, WRITE                         ECO**300
C************************************************************************ECO**310
      IF(KR.LT.NTABLE)GO TO 99                                           ECO   30
      IF(KEY1.NE.0)RETURN                                                ECO   40
      DDEG= 15.0                                                         ECO   50
      R= (XB**2+YB**2+ZB**2)**0.5                                        ECO   60
      RXY= (XB**2+YB**2)**0.5                                            ECO   70
      IF(RXY.GT.1.E-20)GO TO 5                                           ECO   71
      PHI= 3.141592654/2.                                                ECO   72
      GO TO 6                                                            ECO   73
    5 PHI= ABS(ATAN(ZB/RXY))                                             ECO   80
    6 IF(IMODE.EQ.1)GO TO 200                                            ECO   90
```

```
      PHD= PHI*360./6.28318
C DETERMI E QUADRANT OF FLUID CG.
      IF(YB.GT.0..AND.ZB.GE.0.)NQF= 1
      IF(YB.LE.0..AND.ZB.GT.0.)NQF= 2
      IF(YB.LT.0..AND.ZB.LE.0.)NQF= 3
      IF(YB.GE.0..AND.ZB.LT.0.)NQF= 4
C DETERMINE FLUID DIRECTION...QUADRANT OF BETA.
      BETA= Y(2)
      NQB= IQUAD(BETA)
C DETERMINE AXIS INTERCEPT ANGLE BASED ON NQF AND NQB (PHIU)
      GO TO(10,20,30,40),NQF
   10 GO TO(98,50,98,60),NQB
   20 GO TO(50,98,60,98),NQB
   30 GO TO(98,60,98,50),NQB
   40 GO TO(60,98,50,98),NQB
   98 GO TO (91,92,93,94),NQF
   91 IF(ABS(ZB).LT..001.AND.NQB.EQ.1)GO TO 50
      IF(ABS(ZB).LT..001.AND.NQB.EQ.3)GO TO 60
      GO TO 99
   92 IF(ABS(YB).LT..001.AND.NQB.EQ.4)GO TO 50
      IF(ABS(YB).LT..001.AND.NQB.EQ.2)GO TO 60
      GO TO 99
   93 IF(ABS(ZB).LT..001.AND.NQB.EQ.1)GO TO 60
      IF(ABS(ZB).LT..001.AND.NQB.EQ.3)GO TO 50
      GO TO 99
   94 IF(ABS(YB).LT..001.AND.NQB.EQ.4)GO TO 60
      IF(ABS(YB).LT..001.AND.NQB.EQ.2)GO TO 50
      GO TO 99
   50 PHIU= 90.
      GO TO 70
   60 PHIU= 0.0
   70 AM= -1.0
      IF(PHIU.EQ.90.)AM= 1.0
      PHIUR= PHIU*6.28318/360.
      CALL TERP2(TABLE(1,1),PHIUR,TABLE(1,2),RU,NTABLE,1,1,KR,1)
C CHECK ON UPDATE DUE TO SURFACE DEVIATION.
   80 CALL TERP2(TABLE(1,1),PHI,TABLE(1,2),RP,NTABLE,1,1,KR,1)
      IF(ABS(R-RP).LT.(CRIT*RP/100.))GO TO 90
      IF(ABS(PHD-PHIU).LE.20.)KEY1=2
      GO TO 100
C CHECK ON UPDATE DUE TO R GT RTANGENT
   90 IF(R.LT.(RU/COS(PHI)))GO TO 95
      GO TO 100
C NO UPDATE NEEDED
   95 KEY2= 0
      RETURN
C FLUID CG EXCEEDS CRITERIA...UPDATE AAO,CCO.
  100 DRAD= DDEG*6.28318/360.
      PHIN= PHI+(AM*DRAD)
      IF(R.GE.(RU/COS(PHI)))KEY1=1
      IF(R.GE.(RU/COS(PHI)))KEY2=0
      IF(R.GE.(RU/COS(PHI)))RETURN
      IF(KEY1.EQ.0)GOTO 110
C KEY1=1 OR PHI WITHIN 20 DEG OF AXIS USE PHIU FOR UPDATE.
C          EXCEPT WHERE R.GE.(RU/COS(PHI))
C       IN THAT CASE USE CURRENT ELLIPSE
      IF(PHD.GT.89..OR.PHD.LT.1.)KEY1=3
      IF(PHD.GT.89..OR.PHD.LT.1.)KEY2=0
      IF(PHD.GT.89..OR.PHD.LT.1.)RETURN
      PHIN= PHIUR
  110 CALL TERP2(TABLE(1,1),PHIN,TABLE(1,2),RN,NTABLE,1,1,KR,1)
      YN= RN*COS(PHIN)
```

```
      ZN= RN*SIN(PHIN)                                                  ECO  650
      YZ(1,1)= YB**2                                                    ECO  660
      YZ(1,2)= ZB**2                                                    ECO  670
      YZ(2,1)= YN**2                                                    ECO  680
      YZ(2,2)= ZN**2                                                    ECO  690
  130 CALL WRITE(YZ,2,2,2HYZ,2)                                         ECO  700
      CALL INV5(YZ,YZI,2,2)                                             ECO  710
      ACO= YZI(1,1)+YZI(1,2)                                            ECO  720
      CCO= YZI(2,1)+YZI(2,2)                                            ECO  730
      CALL WRITE(YZI,2,2,3HYZI,2)                                       ECO  740
      KEYZ= 1                                                           ECO  750
      RETURN                                                            ECO  760
C IMODE= 1 ,INITIAL DETERMINATION OF AAO,CCO.                           ECO  770
  200 DRAD= DDEG*6.28318/360.                                           ECO  780
      PHIN= PHI+DRAD                                                    ECO  790
      IF(PHIN.GT.(3.14159/2.))PHIN= PHI-DRAD                            ECO  800
      GO TO 110                                                         ECO  810
   99 NERR= 2                                                           ECO  820
      WRITE(6,777)BETA,PHI,NQF,NQB                                      ECO  821
  777 FORMAT(///,2X,2E17.4,2I5)                                         ECO  822
      IF(KR.LT.NTABLE)NERR= 1                                           ECO  830
      CALL ZZBOMB(5HECOEF,NERR)                                         ECO  840
      END                                                               ECO  85*
```

```
      SUBROUTINE SURF(NR,NTHET,VXX,NTABLE,TABLE,KR,IP)
      COMMON/TANK/XL,A,B,PCVOL,FMASS,FDEN,VXOX,VTOT
      DIMENSION TABLE(KR,1)
      NOT= 6
C*********************************************************************
C  SURF COMPUTES THE LOCATION OF THE SURFACE ON WHICH THE FLUID C.G.
C  IS ALLOWED TO MOVE IN A TANK OF DIMENSIONS-XL,A,B WITH FLUID FILL
C  A GIVEN PERCENT (PCVOL) OF TANK VOLUME. THE RESULTANT SURFACE IS
C  STORED IN MATRIX TABLE AS 2 COLUMNS (CYLINDRICAL COORDS).
C         TABLE(NTABLE,1)= ABS(PHI)  RADIANS
C         TABLE(NTABLE,2)= R           LENGTH UNITS
C*********************************************************************
C     CODED BY RL BERRY   MAY 1974  UNDER NAS8-30690
C*********************************************************************
C*********************************************************************
C         M A R T I N   M A R I E T T A   A E R O S P A C E
C*********************************************************************
C**   SUBROUTINE ARGUMENTS
C     --------------------
C        NR= NUMBER OF RADIAL INTEGRATION INCREMENTS ON TANK RADIUS.
C     NTHET= NUMBER OF ANGULAR INTEGRATION INCREMENTS AROUND TANK CIRCUM.
C       VXX= ITERATION CUTOFF (PERCENT OF FLUID VOLUME).
C    NTABLE= NUMBER OF SURFACE LOCATIONS DEFINED FOR PHI= 0 TO 90 DEG.
C     TABLE= MATRIX IN WHICH SURFACE LOCATIONS ARE STORED-SIZE(NTABLE,2).
C        KR= ROW DIMENSION OF TABLE IN CALLING PROGRAM.-GE.NTABLE.
C        IP= 0,NO PRINT OUT.
C          = 1,SURFACE LOCATION PRINTED AND FLUDCG OUTPUT PRINTED.
C          = 2,SURFACE LOCATION PRINTED.
C        XL= LENGTH OF TANK CYLINDRICAL SECTION.                *COMMON
C         A= TANK RADIUS.                                       *COMMON
C         B= HEIGHT OF TANK DOME FROM TOP OF CYLINDRICAL SECTION.*COMMON
C     PCVOL= PERCENT TANK FILL.                                 *COMMON
C**
CZZBOMB-NERROR= 1,KR.LT.NTABLE
C******CALLS SUBROUTINES FLUDCG,PAGEHD,ZZBOMB
C*********************************************************************
      IF(NTABLE.LE.KR)GO TO 5
      GO TO 999
    5 GX= 0.
      TX= -3.14159/2.
      DTX= (3.14159/2.)/(NTABLE-1)
      IPP= IP
      IF(IP.EQ.2) IPP= 0
      DO 10 I=1,NTABLE
      GZ= COS(TX)
      GY= SIN(TX)
      CALL FLUDCG(GX,GY,GZ,NR,NTHET,VXX,XB,YB,ZB,IE,IPP)
      IF(IE.NE.0)TT=TX*360./6.28318
      IF(IE.NE.0)CALL PAGEHD
      IF(IE.NE.0)WRITE(NOT,1000)I,TT,GY,GZ
      R= (YB**2+ZB**2)**.5
      IF(ABS(YB).GT.1.E-20)GO TO 6
      PHI= 3.141592654/2.
      GO TO 7
    6 PHI= ABS(ATAN(ZB/YB))
    7 TABLE(I,1)= PHI
      TABLE(I,2)= R
   10 TX= TX+DTX
      IF(IP.EQ.0)RETURN
      CALL PAGEHD
      WRITE(NOT,1050)
      WRITE(NOT,1100)
```

```
      DO 20 I=1,NTABLE
      TBB= TABLE(I,1)*360./6.28318
   20 WRITE(NOT,1200)TBB,TABLE(I,2)
      RETURN
 1000 FORMAT(/,61HSUBROUTINE SURF--FLUIDCG FAILED TO CONVERGE FOR TABLE
     1VALUE   ,I3,/,5X,8HTHETA X=,F7.5,4H GY=,F12.5,4H GZ=,F12.5)
 1050 FORMAT(/,20X,26HFLUIDCG CONSTRAINT SURFACE,/,20X,26H--------------
     1------------)
 1100 FORMAT(//,20X,10H/PHI(DEG)/,11X,1HR,/,20X,10H----------,10X,3H---)
 1200 FORMAT(20X,F12.5,8X,F12.5)
  999 CALL ZZBOMB(4HSURF,1)
      END
```

```
      SUBROUTINE FLUDCG (GX,GY,GZ,NR,NTHET,VXX,XBAR,YBAR,ZBAR,IE,IP)      FCG   10
      COMMON/TANK/XL,A,B,PCVOL,FMASS,FDEN,VXOX,VTOT                       FCG   20
      DIMENSION AX(3)                                                     FCG   30
      DATA AX/1HX,1HY,1HZ/                                                FCG   40
      REAL MXY,MXZ,MYZ                                                    FCG   50
      NOT= 6                                                              FCG   60
C*********************************************************************FCG** 10
C  FLUDCG CALCULATES THE LOCATION OF THE CENTER OF GRAVITY OF FLUID     FCG** 20
C  IN A CYLINDRICAL TANK WITH HEMI-ELLIPSOIDAL DOMES BASED ON THE      FCG** 30
C  APPLIED ACCELERATION VECTORS GX,GY,GZ. THE PROGRAM OPERATES BY      FCG** 40
C  USING A NEWTON/RAPHSON ITERATION ON THE FLUID VOLUME CONTAINED      FCG** 50
C  IN THE TANK.                                                        FCG** 60
C*********************************************************************FCG** 70
C      CODED BY RL BERRY  USING PROGRAM VOLUME BY J CARPENTER          FCG** 80
C      AS A MODEL.        UNDER NAS8-30690   MAY 1974                  FCG** 90
C*********************************************************************FCG**100
C          M A R T I N   M A R I E T T A   A E R O S P A C E          FCG**110
C*********************************************************************FCG**120
C**    SUBROUTINE ARGUMENTS                                            FCG**130
C      --------------------                                            FCG**140
C GX,GY,GZ= ACCELERATION VECTORS APPLIED TO TANK..Z= AXIAL   (ANY UNITS)FCG**150
C                                                 X,Y= LATERAL         FCG**160
C        NR= NUMBER OF RADIAL INTEGRATION INCREMENTS ON TANK RADIUS.   FCG**170
C     NTHET= NUMBER OF ANGULAR INTERGRATION INCREMENTS AROUND TANK CIRCUMFCG**180
C       VXX= ITERATION CUTOFF (PERCENT OF FLUID VOLUME).               FCG**190
C      XBAR= X COORD. OF FLUID CG LOCATION.                            FCG**200
C      YBAR= YCOORD. OF FLUID CG LOCATION.                             FCG**210
C      ZBAR= COORD. OF FLUID CG LOCATION.                              FCG**220
C        IE= ERROR CODE RETURNED TO CALLING PROGRAM.                   FCG**230
C          = 0, ALGORITHM CONVERGED.                                   FCG**240
C          = 1, ALGORITHM FAILED TO CONVERGE-CG LOCATION MAY BE WRONG. FCG**250
C        IP= 0, NO PRINT OUT.                                          FCG**260
C          = 1, PRINT ALL FLUDCG RESULTS.                              FCG**270
C**    COMMON/TANK/ VARIABLES EXPECTED.                                FCG**280
C      --------------------------------                                FCG**290
C        XL= LENGTH OF TANK CYLINDRICAL SECTION.                       FCG**300
C         A= TANK RADIUS.                                              FCG**310
C         B= HEIGHT OF TANK DOME FROM TOP OF CYLINDRICAL SECTION.      FCG**320
C     PCVOL= PERCENT TANK FILL.LE.100.                                 FCG**330
C**                                                                    FCG**340
C*****CALLS SUBROUTINE PAGEHD                                          FCG**350
C**                                                                    FCG**360
C*****NOTE- SUGGEST...NR= 50                                           FCG**370
C                  NTHET= 50                                           FCG**380
C                    VXX= 2.0                                          FCG**390
C*********************************************************************FCG**400
      M= 2                                                            FCG   80
      IF(ABS(GY).LT.1.E-03)M= 1                                       FCG   90
      IF(ABS(GZ).GE.1.E-03)M= 3                                       FCG  100
      DR= A/FLOAT(NR)                                                 FCG  110
      DT= 2.*3.14159/FLOAT(NTHET)                                     FCG  120
      N1= 20                                                          FCG  130
      ICOUNT=0                                                        FCG  140
      VN= 0.                                                          FCG  170
      VXOX= 3.14159*A**2*XL+(4./3.)*3.14159*B*A**2                    FCG  180
      VTOT= VXOX*PCVOL/100.                                           FCG  190
      VXY= VTOT*VXX/100.                                              FCG  191
      IF(IP.NE.0)CALL PAGEHD                                          FCG  194
      IF(IP.NE.0)WRITE(NOT,1000)GX,GY,GZ,XL,A,B,PCVOL,NR,NTHET,VXY,AX(M)FCG  195
      FMASS= FDEN*VTOT                                                FCG  196
      H1= A/2.                                                        FCG  200
    9 ICOUNT= ICOUNT+1                                                FCG  210
```

```
      V= 0.
      MXY= 0.
      MXZ= 0.
      MYZ= 0.
    7 DO 50 J=1,NR
      DO 60 I=1,NTHET
      R= FLOAT(J)*DR-DR/2.
      TH= FLOAT(I)*DT-DT/2.
      X= R*COS(TH)
      Y= R*SIN(TH)
      UX= SQRT(1.-(R/A)**2)
      ZT= B*UX +XL
      ZB= -1.*(B*UX)
      XMULT= R*DR*DT
      IF(ABS(GZ).LT.1.E-03)GO TO 493
      ZP= H1-(GX/GZ)*X-(GY/GZ)*Y
      IF(ZP.LE.ZB.AND.GZ.GT.0.)GO TO 60
      IF(ZP.GE.ZT.AND.GZ.LT.0.)GO TO 60
      IF(GZ.LT.0.)GO TO 490
      ZA= ZT
      IF(ZP.LE.ZT)ZA= ZP
      V= V+(ZA-ZB)*XMULT
      MXY= MXY+.5*(ZA-ZB)*(ZA+ZB)*XMULT
      MXZ= MXZ+Y*(ZA-ZB)*XMULT
      MYZ= MYZ+X*(ZA-ZB)*XMULT
      GO TO 60
  490 ZA= ZP
      IF(ZP.LE.ZB)ZA= ZB
      V= V+(ZT-ZA)*XMULT
      MXY= MXY+.5*(ZT-ZA)*(ZT+ZA)*XMULT
      MXZ= MXZ+Y*(ZT-ZA)*XMULT
      MYZ= MYZ+X*(ZT-ZA)*XMULT
      GO TO 60
  493 IF(ABS(GY).LT.1.E-03)GO TO 494
      YP= H1-(GX/GY)*X
      IF(Y.GT.YP.AND.GY.GT.0.)GO TO 60
      IF(Y.LT.YP.AND.GY.LT.0.)GO TO 60
      GO TO 10
  494 XP= H1-(GY/GX)*Y
      IF(X.GT.XP.AND.GX.GT.0.)GO TO 60
      IF(X.LT.XP.AND.GX.LT.0.)GO TO 60
   10 V= V+(ZT-ZB)*XMULT
      MXY= MXY+.5*(ZT-ZB)*(ZT+ZB)*XMULT
      MXZ= MXZ+Y*(ZT-ZB)*XMULT
      MYZ= MYZ+X*(ZT-ZB)*XMULT
   60 CONTINUE
   50 CONTINUE
      IF(ABS(V-VN).LT.VXY)GO TO 98
      UPC= V*100./VXOX
      IF(ICOUNT.NE.1) GO TO 20
      HNM1= H1
      VNM1= V
      H1= H1*1.1
      GO TO 30
   20 IF(ICOUNT.GT.2)GO TO 27
      HN= H1
      VN= V
      GO TO 30
   27 VNM1= VN
      VN= V
      HNM1= HN
      HN= H1
```

```
   30 IF(IP.EQ.0)GO TO 40                                               FCG  730
      WRITE(NOT,1100) H1,V,UPC,VN,VNM1,ICOUNT                           FCG  740
   40 IF(ICOUNT.EQ.1)GO TO 9                                            FCG  750
      HNP1= HN-(V-VTOT)*((HN-HNM1)/(VN-VNM1))                           FCG  760
      IF(ICOUNT.GT.NI)GO TO 25                                          FCG  770
      H1= HNP1                                                          FCG  780
      GO TO 9                                                           FCG  790
   98 UPC= V*100./VXOX                                                  FCG  800
      IF(IP.NE.0)WRITE(NOT,1200)H1,V,UPC,ICOUNT                         FCG  810
   25 IF(ICOUNT.GT.NI.AND.IP.NE.0)WRITE(NOT,2000)NI                     FCG  820
      XBAR= MYZ/V                                                       FCG  830
      YBAR= MXZ/V                                                       FCG  840
      ZBAR= (MXY/V)-(XL/2.)                                             FCG  850
      IF(IP.NE.0)WRITE(NOT,1300)XBAR,YBAR,ZBAR                          FCG  860
      IF(IP.NE.0)WRITE(NOT,1400)VXOX,VTOT                               FCG  865
      IE= 0                                                             FCG  870
      IF(ICOUNT.GT.NI)IE= 1                                             FCG  880
      RETURN                                                            FCG  890
C***FORMAT STATEMENTS***                                                 FCG  900
 1000 FORMAT(//////,50X,18HSUBROUTINE FLUIDCG,///,10X,10HINPUT DATA,/,10FCG  910
     1X,10H----------,/,10X,16HTANK ORIENTATION,8X,3HGX=,F12.5,/,34X,3HGFCG  920
     2Y=,F12.5,/,34X,3HGZ=,F12.5,/,10X,13HTANK GEOMETRY,11X,3HXL=,F12.5,FCG  930
     3/,35X,2HA=,F12.5,/,35X,2HB=,F12.5,/,10X,12H$ FLUID FILL,9X,6HPCVOLFCG  940
     4=,F12.5,/,10X,18HINTEGRATION PARAMS,6X,3HNR=,4X,I3,/,31X,6HNTHET=,FCG  950
     54X,I3,/,10X,48HITERATION CUTOFF ABS(V-VN).LT.(VXX*VFLUID/100.)=,  FCG  960
     6F12.5,/////,8X,A1,5H AXIS,12X,5HFLUID,/,7X, 9HINTERCEPT,9X,6HVOLUMFCG  970
     7E,8X,6H$ FILL,10X,4HV(N),12X,6HV(N-1),8X,9HITERATION,/,2(5X,12H---FCG  980
     8---------),5X,7H-------,2(5X,12H------------),5X,9H---------)     FCG  990
 1100 FORMAT(2(5X,F12.5),5X,F7.3,2(5X,F12.5),8X,I3)                     FCG 1000
 1200 FORMAT(2(5X,F12.5),5X,F7.3,42X,I3)                                FCG 1010
 1300 FORMAT(10X,22HFLUID CG IS LOCATED AT,/,10X,5HXBAR=,F12.5,/,10X,   FCG 1020
     15HYBAR=,F12.5,/,10X,5HZBAR=,F12.5)                                FCG 1030
 1400 FORMAT(/,11X,21H****VOLUMES - VTANK=,F12.5,/,25X,7HVFLUID=,F12.5)FCG 1035
 2000 FORMAT(/,9X,20HNO CONVERGENCE AFTER,I3,23H ITERATIONS, BEST GUESS)FCG 1040
      END                                                               FCG 105*
```

```
      SUBROUTINE YDOT
      COMMON/TANK/XL,D,B,PCVOL,FMASS,FDEN,VXOX,VTOT
      COMMON/VECTOR/Y(2),YDT(2),FFRT,      A(3),RHO,QRK(2),PRK(4)
      COMMON/STATE/BETA0,G,H,ENO(3),KEY1,KEY2
      DIMENSION ET(3),AI(3)
C***********************************************************************
C  DEFINES DERIVATIVES FOR USE IN RKADAM
C***********************************************************************
      BETA=Y(2)
      YDT(1)= -1.*FFRT/FMASS-(A(2)*COS(BETA))-(A(3)*SIN(BETA))
      ET(1)= 0.
      ET(2)= G
      ET(3)= H
      CALL VCROSS(ENO,ET,AI,DUM,DUM,AIMAA,DUM)
      YDT(2)= Y(1)/RHO
      IF(AI(1).LT.0.)YDT(2)= -1*YDT(2)
      RETURN
      END
```

```
      SUBROUTINE OUTPT(NU1,NPRINT,ENDT)                                 OUT
      DIMENSION A(22,13),IA(4,13)                                       OUT
C***********************************************************************OUT
C  OUTPT PRINTS THE OUTPUT FOR PROGRAM LAMPS                            OUT
C                                                                       OUT
C***********************************************************************OUT
C     CODED BY RL BERRY   SEPT 1974   UNDER NAS8-30690                  OUT
C***********************************************************************OUT
C        M A R T I N   M A R I E T T A   A E R O S P A C E              OUT
C***********************************************************************OUT
      REWIND NU1                                                        OUT
      NOT= 6                                                            OUT
      CALL PAGEHD                                                       OUT
      WRITE(NOT,2000)                                                   OUT
      NP= 0                                                             OUT
      M= 1                                                              OUT
      READ(NU1)(A(I,M),I=1,22),(IA(J,M),J=1,4)                          OUT
  100 DO 10 I= 1,NPRINT                                                 OUT
      NP= NP+1                                                          OUT
      IF(NP.EQ.NPRINT)GO TO 20                                          OUT
      READ(NU1)T,DUM                                                    OUT
      IF(T.GE.ENDT)GO TO 19                                             OUT
   10 CONTINUE                                                          OUT
      CALL ZZBOMB(5HOUTPT,1)                                            OUT
   19 BACKSPACE NU1                                                     OUT
   20 M= M+1                                                            OUT
      READ(NU1)(A(I,M),I=1,22),(IA(J,M),J=1,4)                          OUT
      IF(A(1,M).GE.ENDT)GO TO 30                                        OUT
      IF(M.GE.13)GO TO 30                                               OUT
      NP= 0                                                             OUT
      GO TO 100                                                         OUT
   30 DO 40 K=1,M                                                       OUT
      WRITE(NOT,2010)(A(I,K),I=1,10)                                    OUT
   40 CONTINUE                                                          OUT
      WRITE(NOT,2020)                                                   OUT
      DO 50 K=1,M                                                       OUT
      WRITE(NOT,2030)A(1,K),(A(I,K),I=11,19)                            OUT
   50 CONTINUE                                                          OUT
      WRITE(NOT,2040)                                                   OUT
      DO 60 K=1,M                                                       OUT
      WRITE(NOT,2050)A(1,K),(A(I,K),I=20,22),(IA(J,K),J=1,4)            OUT
   60 CONTINUE                                                          OUT
      IF(A(1,M).GE.ENDT)GO TO 200                                       OUT
      CALL PAGEHD                                                       OUT
      WRITE(NOT,2000)                                                   OUT
      NP= 0                                                             OUT
      M= 0                                                              OUT
      GO TO 100                                                         OUT
  200 CALL PAGEHD                                                       OUT
      WRITE(NOT,3000)                                                   OUT
      RETURN                                                            OUT
C  FORMATS--OUTPUT                                                      OUT
C***********************************************************************OUT
 2000 FORMAT(///,41X,35HA N A L Y T I C A L   R E S U L T S,//,1X,50H***OUT
     1***********************************************,12HSYSTEM STATE,54OUT
     2H*****************************************************,/,4X,4HTTIMOUT
     3E,6X,5HVTDOT,8X,2HVT,10X,7HBETADOT,5X,4HBETA,10X,1HX,11X,1HY,11X,1OUT
     4HZ,11X,1HR,10X,3HPHI,/,1X,11(10H----------),5H-----,/)            OUT
 2010 FORMAT(1X,F9.3,3(3X,E10.3),2X,F7.2,3X,4(2X,E10.3),2X,F7.2)        OUT
 2020 FORMAT(/,13X,22H****APPLIED ACCEL*****,3X,33H*************SURFACE*OUT
     1************,4X,18H******TANGENT*****,6X,18H*******NORMAL*****,/, OUT
     24X,4HTIME,9X,2HAY,10X,2HAZ,10X,3HACO,9X,3HCCO,9X,3HRHO,9X,1HJ,11X,OUT
```

ORIGINAL PAGE IS
OF POOR QUALITY

```
     31HK,11X,1HJ,11X,1HK,/,1X,11(10H----------),6H------,/)          OUT
2030 FORMAT(1X,F9.3,1X,5(2X,E10.3),4X,4(F6.3,6X))                     OUT
2040 FORMAT(/,13X,24H****FLUID FORCES ON TANK,4(4H****),14X,18H*********OUT
     1KEYS******,12X,11H*QUADRANTS*,/,4X,4HTIME,9X,6HFY     ,8X,6HFZ   ,OUT
     25X,8HMX      ,17X,4HKEY1,10X,4HKEY2,12X,3HNQB,5X,3HNQF,/,1X,27(4H-OUT
     3---),/)                                                         OUT
2050 FORMAT(1X,F9.3,1X,3(2X,E12.4),13X,I5,9X,I5,11X,I5,3X,I5)         OUT
3000 FORMAT(///////,38X,8(4H****),1H*,/,38X,33H**LAMPS SUCCESSFULLY TEROUT
     1MINATED**,/,38X,8(4H****),1H*)                                  OUT
      END                                                             OUT
```

```
      SUBROUTINE TLMPLT(NKT,NPL,TR)
      DIMENSION PLO(200,11),PT(4)
      DATA PT(1),PT(2),PT(3),PT(4)/10HLARGE AMPL,10HITUDE SLOS,10HH SIMU
     $LATI,2HON/
C*********************************************************************
C     PLOTS OUTPUT
C*********************************************************************
      XS=-1.*TR
      XD=(2.*TR)/10.
      XNAME1=3HSEC
      XNAME2=1HY
      YNAM1=5HACCEL
      YNAM2=3HVEL
      YNAM3=6HBETADT
      YNAM4=4HBETA
      YNAM5=3HPHI
      YNAM6=1HZ
      YNAM7=2HFY
      YNAM8=2HFZ
      YNAM9=2HMX
      REWIND NPL
      NEND=200
      IF(NKT.LT.200)NEND=NKT
      IDEL=NKT/205+1
      KN=0
      IN=0
      DO 10 I=1,NKT
      KN=KN+1
      IF(I.EQ.1)GOTO 20
      IF(KN.EQ.IDEL)GOTO 20
      READ(NPL)DUM
      GOTO 10
   20 IN=IN+1
      READ(NPL)(PLO(IN,J),J=1,11)
      KN=0
      IF(IN.EQ.NEND)GOTO 30
   10 CONTINUE
   30 CALL PLOT1(PLO(1,1),PLO(1,2),IN,1,0.,.2,XNAME1,YNAM1,PT,1,1,1,200)
      CALL PLOT1(PLO(1,1),PLO(1,3),IN,1,0.,.2,XNAME1,YNAM2,PT,1,1,1,200)
      CALL PLOT1(PLO(1,1),PLO(1,4),IN,1,0.,.2,XNAME1,YNAM3,PT,1,1,1,200)
      CALL PLOT1(PLO(1,1),PLO(1,5),IN,1,0.,.2,XNAME1,YNAM4,PT,1,1,1,200)
      CALL PLOT1(PLO(1,1),PLO(1,6),IN,1,0.,.2,XNAME1,YNAM5,PT,1,1,1,200)
      CALL PLOT1(PLO(1,1),PLO(1,9),IN,1,0.,.2,XNAME1,YNAM7,PT,1,1,1,200)
      CALL PLOT1(PLO(1,1),PLO(1,10),IN,1,0.,.2,XNAME1,YNAM8,PT,1,1,1,200
     $)
      CALL PLOT1(PLO(1,1),PLO(1,11),IN,1,0.,.2,XNAME1,YNAM9,PT,1,1,1,200
     $)
      CALL PLOT1(PLO(1,7),PLO(1,8),IN,1,XS,XD,XNAME2,YNAM6,PT,1,1,1,200)
      RETURN
      END
```

C-2

FORMA

NAME R. L. BERRY

PAGE 1 OF 1

SAMPLE INPUT FOR PROGRAM LAMPS

```
TEST16    RL BERRY
CHECK ØUT ØF PRØGRAM LAMPS USING TEST 16
FC43 FLUID
   1.4       2.5        2.5     25.0      45.0      1.78E-04
    50  50   20    1    2    1
   2.0       2.0       0.01      2.0
 999.0     999.0       0.0       0.0    4.5850E-03
   TEST CASE 16 TØ CHECK ØUT LAMPS
      THETA= 45.0 DEG
  FØRCE(V)= -30 LB
  FØRCE(L)= .75 LB
      TANK= 25 PERCENT FULL
0000000000
ACCEL    3   3
    1    1    0.0                 8.33              386.04
    2    1    0.1                 8.33              -35.205
    3    1    2.0                 8.33              -35.205
0000000000
STØP
```

DEN 410740 (6-74)

SAMPLE OUTPUT

RUN NO. TEST16 DATE 03FE75 PAGE NO. 1

RUN BY RL BERRY

17.44.27 CLOCK TIME
13.335 SEC. CPTIME
21 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

LARGE AMPLITUDE SLOSH -- L A M P S -- ANALYTICAL SIMULATION

I N P U T D A T A
****

XL=	1.40
TR=	2.50
TO=	2.50
PCVOL=	25.00
THETAX=	45.00
FOEN=	1.78E-04
NR=	50
NTHET=	50
VXX=	2.00
NTABLE=	20
IPRINT=	1
NPRINT=	2
NPLOT=	1
SMASS=	4.5850E-03
CRIT=	2.00
DELTAT=	.010
ENDT=	2.000
AYI=	999.0000
AZI=	999.0000
XMU=	0.
XNU=	0.

```
                                                                17.44.27 CLOCK  TIME
CHECK OUT OF PROGRAM LAMPS USING TEST 16                          13.391 SEC. CPTIME
FC43 FLUID                                                        21     SEC. PPTIME

          TEST CASE 16 TO CHECK OUT LAMPS
            THETA= 45.0 DEG
         FORCE(V)= -30 LB
         FORCE(L)= .75 LB
             TANK= 25 PERCENT FULL
```

```
RUN NO. TEST16                                  DATE 03FE75                             PAGE NO.    3
                                                RUN BY RL BERRY
                                                                               17.44.27 CLOCK  TIME
       CHECK OUT OF PROGRAM LAMPS USING TEST 16                                  13.440 SEC. CPTIME
       FC43 FLUID                                                                21     SEC. PPTIME

CARD INPUT MATRIX ACCEL    (   3 X   3 )                                          -01

   1   1   0.                8.33000000E+00   3.86040000E+02
   2   1   1.00000000E-01    8.33000000E+00  -3.52050000E+01
   3   1   2.00000000E+00    8.33000000E+00  -3.52050000E+01

END OF READ.
```

18.03.43 CLOCK TIME
153.234 SEC. CPTIME
22 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

FLUIDCG CONSTRAINT SURFACE

/PHI(DEG)/	R
.00000	1.49893
7.60640	1.50945
15.02653	1.52377
22.17221	1.54664
29.07728	1.57676
35.51676	1.61161
41.49300	1.64925
47.01143	1.68781
52.06718	1.72429
56.68401	1.75989
60.90190	1.79232
64.73810	1.82061
68.28325	1.84512
71.61745	1.86605
74.80671	1.88317
77.89947	1.89682
80.93902	1.90734
83.96231	1.91478
86.99692	1.91947
90.00008	1.92103

18.03.43 CLOCK TIME
153.303 SEC. CPTIME
22 SEC. PPTIME

CHECK CUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

SUBROUTINE FLUIDCG

```
INPUT DATA
----------
TANK ORIENTATION          GX=      0.       !
                          GY=       .70711!
                          GZ=       .70711!
TANK GEOMETRY             XL=      1.40000!
                           A=      2.50000!
                           B=      2.50000!
$ FLUID FILL           PCVOL=     25.00000!
INTEGRATION PARAMS        NR=      50
                       NTHET=      50
ITERATION CUTOFF  ABS(V-VN).LT.(VXX*VFLUID/100.)=        .46469
```

Z AXIS INTERCEPT	FLUID VOLUME	$ FILL	V(N)	V(N-1)	ITERATION
1.37500	55.69973	59.932	0.	55.69973	1
1.37500	57.75248	62.140	57.75248	55.69973	2
-.72693	23.51920	25.306	23.51920	57.75248	3
-.74440	23.26375	25.031			4

```
FLUID CG IS LOCATED AT
XBAR=     -.00000
YBAR=     -.91928
ZBAR=    -1.52018

*****VOLUMES - VTANK=    92.93870
               VFLUID=   23.23468

***INITIAL FLUIC CG LOCATION***
```

```
RUN NO. TEST16                              DATE 03FE75                                   PAGE NO.    6
                                          RUN BY RL BERRY
                                                                                    18.04.24 CLOCK  TIME
      CHECK OUT OF PROGRAM LAMPS USING TEST 16                                       159.859 SEC. CPTIME
      FC43 FLUID                                                                      22     SEC. PPTIME

OUTPUT MATRIX YZ        (   2 X   2 )

              ( 1)       ( 2)       ( 3)       ( 4)       ( 5)       ( 6)       ( 7)       ( 8)       ( 9)       (10)

   1    1   8.451E-01  2.311E+00
   2    1   2.734E-01  3.255E+00

END OF WRITE.
```

```
RUN NO. TEST16                                  DATE 03FE75                                PAGE NO.    7
                                                RUN BY RL BERRY
                                                                                    18.04.24 CLOCK  TIME
       CHECK OUT OF PROGRAM LAMPS USING TEST 16                                     159.896 SEC. CPTIME
       FC43 FLUID                                                                    22      SEC. PPTIME

            ( 1)      ( 2)      ( 3)      ( 4)      ( 5)      ( 6)      ( 7)      ( 8)      ( 9)      (10)

       SUBROUTINE INV5 HAS CALCULATED THE DATA BELOW


       THE (A**-1)*(A) INVERSION CHECK GIVES


       THE DIAGONAL ELEMENTS ARE

          1.00000000 1.00000000

       THE MAXIMUM OFF-DIAGONAL ELEMENT IS  8.882E-16  AT (  2,  1)
```

```
RUN NO. TEST16                              DATE 03FE75                                   PAGE NO.    8
                                          RUN BY RL BERRY
                                                                                  18.04.24 CLOCK  TIME
       CHECK OUT OF PROGRAM LAMPS USING TEST 16                                  159.928 SEC. CPTIME
       FC43 FLUID                                                                 22      SEC. PPTIME

OUTPUT MATRIX YZI     (   2 X   2 )

            ( 1)      ( 2)      ( 3)      ( 4)      ( 5)      ( 6)      ( 7)      ( 8)      ( 9)      (10)

   1   1    1.536E+00 -1.091E+00
   2   1   -1.290E-01  3.989E-01

END OF WRITE.
```

```
RUN NO. TEST16                         DATE 03FE75                          PAGE NO.    9
                                      RUN BY RL BERRY
                                                                   18.04.24 CLOCK  TIME
      CHECK CUT OF PROGRAM LAMPS USING TEST 16                     159.958 SEC. CPTIME
      FC43 FLUID                                                    22      SEC. PPTIME


          TANK AND FLUID CHARACTERISTICS
          ------------------------------
          TANK VOLUME=       92.9387  CU UNITS

         FLUID VOLUME=       23.2347  CU UNITS

          FLUID MASS=          .0041  F -SEC**2/L**4
```

18.05.16 CLOCK TIME
164.242 SEC. CPTIME
35 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

A N A L Y T I C A L   R E S U L T S

	******	******	******	SYSTEM STATE	******	******	******	******	******
TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
0.	8.698E+00	0.	0.	135.05	0.	-9.193E-01	-1.520E+00	1.777E+00	238.84
.020	8.373E+00	1.549E-01	-5.477E+00	135.01	0.	-9.202E-01	-1.519E+00	1.776E+00	238.80
.040	7.712E+00	3.005E-01	-1.061E+01	134.86	0.	-9.231E-01	-1.516E+00	1.775E+00	238.67
.060	7.200E+00	4.358E-01	-1.536E+01	134.63	0.	-9.277E-01	-1.512E+00	1.774E+00	238.46
.080	7.239E+00	5.674E-01	-1.992E+01	134.31	0.	-9.341E-01	-1.505E+00	1.772E+00	238.18
.100	8.197E+00	7.088E-01	-2.477E+01	133.91	0.	-9.420E-01	-1.497E+00	1.769E+00	237.82
.120	9.297E+00	8.724E-01	-3.031E+01	133.42	0.	-9.518E-01	-1.487E+00	1.765E+00	237.37
.140	9.659E+00	1.043E+00	-3.599E+01	132.83	0.	-9.636E-01	-1.474E+00	1.761E+00	236.83
.160	1.003E+01	1.221E+00	-4.178E+01	132.13	0.	-9.774E-01	-1.459E+00	1.756E+00	236.18
.180	1.057E+01	1.407E+00	-4.767E+01	131.32	0.	-9.932E-01	-1.441E+00	1.750E+00	235.43
.200	1.112E+01	1.603E+00	-5.368E+01	130.41	0.	-1.011E+00	-1.421E+00	1.744E+00	234.57
.220	1.173E+01	1.808E+00	-5.981E+01	129.40	0.	-1.031E+00	-1.397E+00	1.736E+00	233.58
.240	1.240E+01	2.026E+00	-6.605E+01	128.27	0.	-1.052E+00	-1.370E+00	1.728E+00	232.47

	****APPLIED ACCEL*****		*************	SURFACE	*************	******TANGENT*****		*******NORMAL*****	
TIME	AY	AZ	ACC	CCO	RHO	J	K	J	K
0.	2.789E+02	2.671E+02	4.454E-01	2.698E-01	1.620E+00	-.708	.706	-.706	-.708
.020	2.193E+02	2.075E+02	4.454E-01	2.698E-01	1.621E+00	-.707	.707	-.707	-.707
.040	1.597E+02	1.479E+02	4.454E-01	2.698E-01	1.624E+00	-.705	.709	-.709	-.705
.060	1.001E+02	8.836E+01	4.454E-01	2.698E-01	1.629E+00	-.703	.712	-.712	-.703
.080	4.057E+01	2.879E+01	4.454E-01	2.698E-01	1.635E+00	-.699	.716	-.716	-.699
.100	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.644E+00	-.694	.720	-.720	-.694
.120	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.655E+00	-.687	.726	-.726	-.687
.140	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.667E+00	-.680	.733	-.733	-.680
.160	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.683E+00	-.671	.742	-.742	-.671
.180	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.701E+00	-.660	.751	-.751	-.660
.200	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.721E+00	-.648	.761	-.761	-.648
.220	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.744E+00	-.635	.773	-.773	-.635
.240	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.771E+00	-.619	.785	-.785	-.619

	****FLUID FORCES ON TANK****		************	********KEYS******		*QUADRANTS*	
TIME	FY	FZ	MX	KEY1	KEY2	NQB	NQF
0.	-2.4089E+00	-2.3570E+00	-6.7723E-01	0	0	2	3
.020	-1.8899E+00	-1.8361E+00	-5.2958E-01	0	0	2	3
.040	-1.3716E+00	-1.3146E+00	-3.8208E-01	0	0	2	3
.060	-8.5282E-01	-7.9377E-01	-2.3454E-01	0	0	2	3
.080	-3.3233E-01	-2.7486E-01	-8.6805E-02	0	0	2	3
.100	1.9084E-01	2.4100E-01	6.1193E-02	0	0	2	3
.120	1.9100E-01	2.3944E-01	6.0864E-02	0	0	2	3
.140	1.9113E-01	2.3754E-01	6.0424E-02	0	0	2	3
.160	1.9121E-01	2.3528E-01	5.9853E-02	0	0	2	3
.180	1.9120E-01	2.3265E-01	5.9122E-02	0	0	2	3
.200	1.9105E-01	2.2964E-01	5.8202E-02	0	0	2	3
.220	1.9074E-01	2.2624E-01	5.7059E-02	0	0	2	3
.240	1.9019E-01	2.2248E-01	5.5655E-02	0	0	2	3

18.05.18 CLOCK TIME
164.652 SEC. CPTIME
36 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

A N A L Y T I C A L   R E S U L T S

TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
.260	1.314E+01	2.256E+00	-7.241E+01	127.02	0.	-1.076E+00	-1.340E+00	1.718E+00	231.22
.280	1.393E+01	2.500E+00	-7.886E+01	125.66	0.	-1.102E+00	-1.305E+00	1.708E+00	229.83
.300	1.478E+01	2.758E+00	-8.541E+01	124.19	0.	-1.129E+00	-1.266E+00	1.696E+00	228.27
.320	1.570E+01	3.033E+00	-9.204E+01	122.60	0.	-1.158E+00	-1.222E+00	1.683E+00	226.55
.340	1.666E+01	3.324E+00	-9.875E+01	120.89	0.	-1.188E+00	-1.173E+00	1.670E+00	224.63
.360	1.768E+01	3.634E+00	-1.055E+02	119.05	0.	-1.220E+00	-1.118E+00	1.655E+00	222.52
.380	1.875E+01	3.962E+00	-1.123E+02	117.10	0.	-1.252E+00	-1.057E+00	1.633E+00	220.18
.400	1.986E+01	4.310E+00	-1.193E+02	115.02	0.	-1.285E+00	-9.900E-01	1.622E+00	217.61
.420	2.100E+01	4.678E+00	-1.262E+02	112.82	0.	-1.318E+00	-9.154E-01	1.605E+00	214.78
.440	2.218E+01	5.067E+00	-1.334E+02	110.49	0.	-1.351E+00	-8.331E-01	1.587E+00	211.67
.460	2.339E+01	5.478E+00	-1.406E+02	108.03	0.	-1.382E+00	-7.428E-01	1.569E+00	208.25
.480	2.461E+01	5.911E+00	-1.482E+02	105.44	0.	-1.412E+00	-6.438E-01	1.552E+00	204.51
.500	2.585E+01	6.365E+00	-1.561E+02	102.71	0.	-1.439E+00	-5.357E-01	1.536E+00	200.42

	APPLIED ACCEL		SURFACE			TANGENT		NORMAL	
TIME	AY	AZ	ACO	CCO	RHO	J	K	J	K
.260	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.800E+00	-.602	.798	-.798	-.602
.280	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.833E+00	-.583	.812	-.812	-.583
.300	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.869E+00	-.562	.827	-.827	-.562
.320	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.908E+00	-.539	.842	-.842	-.539
.340	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.951E+00	-.513	.858	-.858	-.513
.360	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.997E+00	-.486	.874	-.874	-.486
.380	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.045E+00	-.456	.890	-.890	-.456
.400	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.097E+00	-.423	.906	-.906	-.423
.420	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.150E+00	-.388	.922	-.922	-.388
.440	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.204E+00	-.350	.937	-.937	-.350
.460	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.259E+00	-.310	.951	-.951	-.310
.480	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.311E+00	-.266	.964	-.964	-.266
.500	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.361E+00	-.220	.975	-.975	-.220

	FLUID FORCES ON TANK			KEYS		QUADRANTS	
TIME	FY	FZ	MX	KEY1	KEY2	NQB	NQF
.260	1.8932E-01	2.1822E-01	5.3954E-02	0	0	2	3
.280	1.8808E-01	2.1359E-01	5.1918E-02	0	0	2	3
.300	1.8638E-01	2.0857E-01	4.9513E-02	0	0	2	3
.320	1.8411E-01	2.0316E-01	4.6710E-02	0	0	2	3
.340	1.8120E-01	1.9741E-01	4.3488E-02	0	0	2	3
.360	1.7752E-01	1.9136E-01	3.9841E-02	0	0	2	3
.380	1.7298E-01	1.8507E-01	3.5779E-02	0	0	2	3
.400	1.6744E-01	1.7863E-01	3.1334E-02	0	0	2	3
.420	1.6077E-01	1.7213E-01	2.6569E-02	0	0	2	3
.440	1.5286E-01	1.6571E-01	2.1583E-02	0	0	2	3
.460	1.4354E-01	1.5951E-01	1.6515E-02	0	0	2	3
.480	1.3267E-01	1.5372E-01	1.1556E-02	0	0	2	3
.500	1.2007E-01	1.4857E-01	6.9558E-03	0	0	2	3

18.05.21 CLOCK TIME
165.064 SEC. CPTIME
38 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

A N A L Y T I C A L   R E S U L T S

SYSTEM STATE

TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
.520	2.709E+01	6.843E+00	-1.645E+02	99.83	0.	-1.463E+00	-4.183E-01	1.521E+00	195.96
.540	2.832E+01	7.342E+00	-1.736E+02	96.79	0.	-1.481E+00	-2.913E-01	1.510E+00	191.13
.560	2.954E+01	7.864E+00	-1.836E+02	93.58	0.	-1.494E+00	-1.544E-01	1.502E+00	185.90
.580	3.072E+01	8.407E+00	-1.950E+02	90.18	0.	-1.498E+00	-7.686E-03	1.498E+00	180.29
.600	3.187E+01	8.971E+00	-2.080E+02	86.55	0.	-1.494E+00	1.487E-01	1.501E+00	174.32
.620	3.296E+01	9.556E+00	-2.233E+02	82.66	0.	-1.478E+00	3.142E-01	1.511E+00	168.00
.640	3.396E+01	1.016E+01	-2.415E+02	78.47	0.	-1.449E+00	4.882E-01	1.529E+00	161.39
.660	3.485E+01	1.078E+01	-2.637E+02	73.90	0.	-1.405E+00	6.693E-01	1.556E+00	154.53
.680	3.556E+01	1.142E+01	-2.910E+02	68.88	0.	-1.342E+00	8.559E-01	1.592E+00	147.47
.700	3.604E+01	1.206E+01	-3.252E+02	63.28	0.	-1.258E+00	1.045E+00	1.636E+00	140.28
.720	3.617E+01	1.271E+01	-3.682E+02	56.98	0.	-1.150E+00	1.234E+00	1.687E+00	132.99
.740	3.578E+01	1.336E+01	-4.225E+02	49.77	0.	-1.015E+00	1.417E+00	1.742E+00	125.61
.760	3.462E+01	1.400E+01	-4.901E+02	41.43	0.	-8.484E-01	1.587E+00	1.799E+00	118.13

TIME	APPLIED ACCEL AY	APPLIED ACCEL AZ	SURFACE ACO	SURFACE CCO	SURFACE RHO	TANGENT J	TANGENT K	NORMAL J	NORMAL K
.520	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.404E+00	-.171	.985	-.985	-.171
.540	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.440E+00	-.118	.993	-.993	-.118
.560	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.464E+00	-.063	.998	-.998	-.063
.580	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.473E+00	-.003	1.000	-1.000	-.003
.600	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.464E+00	.060	.998	-.998	.060
.620	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.434E+00	.128	.992	-.992	.128
.640	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.380E+00	.200	.980	-.980	.200
.660	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.299E+00	.277	.961	-.961	.277
.680	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.190E+00	.360	.933	-.933	.360
.700	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.055E+00	.450	.893	-.893	.450
.720	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.897E+00	.545	.838	-.838	.545
.740	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.725E+00	.646	.763	-.763	.646
.760	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.550E+00	.750	.662	-.662	.750

TIME	FLUID FORCES ON TANK FY	FZ	MX	KEYS KEY1	KEY2	QUADRANTS NQB	NQF
.520	1.0554E-01	1.4433E-01	3.0355E-03	0	0	2	3
.540	8.8848E-02	1.4135E-01	1.9714E-04	0	0	2	3
.560	6.9723E-02	1.4005E-01	-1.0593E-03	0	0	2	3
.580	4.7841E-02	1.4102E-01	-1.1902E-04	0	0	2	3
.600	2.2824E-02	1.4502E-01	3.7679E-03	0	0	1	2
.620	-5.7655E-03	1.5311E-01	1.1504E-02	0	0	1	2
.640	-3.8400E-02	1.6676E-01	2.4152E-02	0	0	1	2
.660	-7.5512E-02	1.8809E-01	4.2905E-02	0	0	1	2
.680	-1.1732E-01	2.2014E-01	6.8968E-02	0	0	1	2
.700	-1.6342E-01	2.6725E-01	1.0322E-01	0	0	1	2
.720	-2.1188E-01	3.3550E-01	1.4541E-01	0	0	1	2
.740	-2.5750E-01	4.3271E-01	1.9243E-01	0	0	1	2
.760	-2.8668E-01	5.6701E-01	2.3503E-01	0	0	1	2

18.05.23 CLOCK TIME
165.464 SEC. CPTIME
39 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

A N A L Y T I C A L R E S U L T S

SYSTEM STATE									
TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
.780	3.235E+01	1.461E+01	-5.712E+02	31.71	0.	-6.494E-01	1.735E+00	1.852E+00	110.52
.800	2.355E+01	1.516E+01	-6.603E+02	20.42	0.	-4.171E-01	1.849E+00	1.895E+00	102.71
.820	2.291E+01	1.563E+01	-7.408E+02	7.60	0.	-1.547E-01	1.915E+00	1.921E+00	94.62
.840	1.551E+01	1.598E+01	-7.852E+02	353.70	0.	1.283E-01	1.918E+00	1.922E+00	86.17
.860	7.121E+00	1.619E+01	-7.705E+02	339.66	0.	4.153E-01	1.850E+00	1.896E+00	77.34
.880	-1.126E+00	1.625E+01	-7.026E+02	326.53	0.	6.857E-01	1.712E+00	1.844E+00	68.17
.900	-8.338E+00	1.617E+01	-6.121E+02	314.91	0.	9.223E-01	1.517E+00	1.776E+00	58.71
.920	-1.439E+01	1.596E+01	-5.264E+02	304.87	0.	1.116E+00	1.284E+00	1.701E+00	48.99
.940	-1.924E+01	1.566E+01	-4.569E+02	296.18	0.	1.267E+00	1.028E+00	1.632E+00	39.06
.960	-2.314E+01	1.528E+01	-4.046E+02	288.54	0.	1.376E+00	7.618E-01	1.573E+00	28.97
.980	-2.630E+01	1.483E+01	-3.664E+02	281.67	0.	1.448E+00	4.938E-01	1.530E+00	18.83
1.000	-2.888E+01	1.433E+01	-3.391E+02	275.36	0.	1.488E+00	2.302E-01	1.505E+00	8.79
1.020	-3.097E+01	1.379E+01	-3.201E+02	269.43	0.	1.498E+00	-2.469E-02	1.498E+00	359.06

	APPLIED ACCEL		SURFACE			TANGENT		NORMAL	
TIME	AY	AZ	ACO	CCO	RHO	J	K	J	K
.780	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.386E+00	.851	.526	-.526	.851
.800	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.256E+00	.937	.349	-.349	.937
.820	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.178E+00	.991	.132	-.132	.991
.840	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.175E+00	.994	-.110	.110	.994
.860	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.255E+00	.938	-.348	.348	.938
.880	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.413E+00	.834	-.552	.552	.834
.900	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.623E+00	.706	-.708	.708	.706
.920	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.852E+00	.572	-.820	.820	.572
.940	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.068E+00	.441	-.897	.897	.441
.960	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.248E+00	.318	-.948	.948	.318
.980	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.378E+00	.202	-.978	.979	.202
1.000	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.452E+00	.093	-.996	.996	.093
1.020	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.473E+00	-.010	-1.000	1.000	-.010

	FLUID FORCES ON TANK			KEYS		QUADRANTS	
TIME	FY	FZ	MX	KEY1	KEY2	NQB	NQF
.780	-2.8351E-01	7.4106E-01	2.5343E-01	0	0	1	2
.800	-2.0982E-01	9.3871E-01	2.1639E-01	0	0	1	2
.820	-4.1823E-02	1.1081E+00	9.7316E-02	0	0	1	2
.840	2.0096E-01	1.1719E+00	-8.6049E-02	0	0	4	1
.860	4.3922E-01	1.0911E+00	-2.5667E-01	0	0	4	1
.880	5.9713E-01	9.1249E-01	-3.4405E-01	0	0	4	1
.900	6.6313E-01	7.1524E-01	-3.4443E-01	0	0	4	1
.920	6.6777E-01	5.4573E-01	-2.9383E-01	0	0	4	1
.940	6.4206E-01	4.1400E-01	-2.2486E-01	0	0	4	1
.960	6.0440E-01	3.1464E-01	-1.5531E-01	0	0	4	1
.980	5.6347E-01	2.3954E-01	-9.2704E-02	0	0	4	1
1.000	5.2279E-01	1.8198E-01	-3.9521E-02	0	0	4	1
1.020	4.8349E-01	1.3219E-01	3.8573E-03	0	0	3	4

RUN BY RL BERRY

18.05.26 CLOCK TIME
165.880 SEC. CPTIME
40 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

A N A L Y T I C A L   R E S U L T S

SYSTEM STATE

TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
1.040	-3.267E+01	1.322E+01	-3.073E+02	263.77	0.	1.484E+00	-2.676E-01	1.508E+00	349.78
1.060	-3.400E+01	1.262E+01	-2.993E+02	258.27	0.	1.448E+00	-4.961E-01	1.530E+00	341.09
1.080	-3.501E+01	1.199E+01	-2.949E+02	252.88	0.	1.393E+00	-7.085E-01	1.563E+00	333.05
1.100	-3.571E+01	1.136E+01	-2.931E+02	247.52	0.	1.323E+00	-9.035E-01	1.602E+00	325.67
1.120	-3.609E+01	1.071E+01	-2.931E+02	242.18	0.	1.240E+00	-1.080E+00	1.645E+00	318.94
1.140	-3.616E+01	1.006E+01	-2.939E+02	236.82	0.	1.147E+00	-1.238E+00	1.688E+00	312.82
1.160	-3.592E+01	9.405E+00	-2.948E+02	231.44	0.	1.047E+00	-1.377E+00	1.730E+00	307.23
1.180	-3.535E+01	8.761E+00	-2.949E+02	226.04	0.	9.412E-01	-1.498E+00	1.769E+00	302.14
1.200	-3.447E+01	8.130E+00	-2.935E+02	220.66	0.	8.329E-01	-1.600E+00	1.804E+00	297.50
1.220	-3.331E+01	7.517E+00	-2.897E+02	215.33	0.	7.239E-01	-1.685E+00	1.834E+00	293.24
1.240	-3.188E+01	6.928E+00	-2.833E+02	210.10	0.	6.162E-01	-1.755E+00	1.860E+00	289.35
1.260	-3.024E+01	6.367E+00	-2.741E+02	205.01	0.	5.115E-01	-1.809E+00	1.880E+00	285.79
1.280	-2.844E+01	5.836E+00	-2.621E+02	200.13	0.	4.111E-01	-1.851E+00	1.896E+00	282.52

TIME	APPLIED ACCEL AY	APPLIED ACCEL AZ	SURFACE ACO	SURFACE CCO	SURFACE RHO	TANGENT J	TANGENT K	NORMAL J	NORMAL K
1.040	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.445E+00	-.109	-.994	.994	-.109
1.060	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.377E+00	-.203	-.979	.979	-.203
1.080	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.278E+00	-.294	-.956	.956	-.294
1.100	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.158E+00	-.382	-.924	.924	-.382
1.120	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	2.027E+00	-.467	-.884	.884	-.467
1.140	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.894E+00	-.547	-.837	.837	-.547
1.160	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.764E+00	-.623	-.782	.782	-.623
1.180	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.643E+00	-.694	-.720	.720	-.694
1.200	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.535E+00	-.759	-.652	.652	-.759
1.220	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.442E+00	-.816	-.578	.578	-.816
1.240	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.364E+00	-.865	-.501	.501	-.865
1.260	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.301E+00	-.906	-.423	.423	-.906
1.280	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.253E+00	-.939	-.344	.344	-.939

TIME	FLUID FORCES ON TANK FY	FZ	MX	KEYS KEY1	KEY2	QUADRANTS NQB	NQF
1.040	4.4569E-01	1.0197E-01	3.7813E-02	0	0	3	4
1.060	4.0910E-01	7.4301E-02	6.2954E-02	0	0	3	4
1.080	3.7337E-01	5.2953E-02	7.9930E-02	0	0	3	4
1.100	3.3819E-01	3.7275E-02	8.9401E-02	0	0	3	4
1.120	3.0341E-01	2.7012E-02	9.2082E-02	0	0	3	4
1.140	2.6911E-01	2.2149E-02	8.8810E-02	0	0	3	4
1.160	2.3563E-01	2.2764E-02	8.0612E-02	0	0	3	4
1.180	2.0358E-01	2.8870E-02	6.8744E-02	0	0	3	4
1.200	1.7380E-01	4.0256E-02	5.4662E-02	0	0	3	4
1.220	1.4723E-01	5.6372E-02	3.9921E-02	0	0	3	4
1.240	1.2472E-01	7.6289E-02	2.5999E-02	0	0	3	4
1.260	1.0691E-01	9.8764E-02	1.41[illegible]E-02	0	0	3	4
1.280	9.4003E-02	1.2640E-01	5.0137E-03	0	0	3	4

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

18.05.31 CLOCK TIME
166.298 SEC. CPTIME
41 SEC. PPTIME

A N A L Y T I C A L   R E S U L T S

SYSTEM STATE

TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
1.300	-2.653E+01	5.339E+00	-2.480E+02	195.49	0.	3.159E-01	-1.882E+00	1.908E+00	279.53
1.320	-2.459E+01	4.877E+00	-2.321E+02	191.13	0.	2.268E-01	-1.903E+00	1.916E+00	276.80
1.340	-2.265E+01	4.450E+00	-2.154E+02	187.07	0.	1.440E-01	-1.916E+00	1.922E+00	274.30
1.360	-2.076E+01	4.057E+00	-1.984E+02	183.32	0.	6.762E-02	-1.923E+00	1.924E+00	272.01
1.380	-1.894E+01	3.698E+00	-1.816E+02	179.88	0.	-2.368E-03	-1.925E+00	1.925E+00	269.93
1.400	-1.723E+01	3.371E+00	-1.655E+02	176.75	0.	-6.626E-02	-1.923E+00	1.924E+00	268.03
1.420	-1.562E+01	3.074E+00	-1.504E+02	173.89	0.	-1.244E-01	-1.918E+00	1.922E+00	266.29
1.440	-1.413E+01	2.805E+00	-1.365E+02	171.30	0.	-1.772E-01	-1.912E+00	1.920E+00	264.70
1.460	-1.275E+01	2.562E+00	-1.237E+02	168.95	0.	-2.251E-01	-1.903E+00	1.916E+00	263.25
1.480	-1.146E+01	2.343E+00	-1.121E+02	166.82	0.	-2.686E-01	-1.894E+00	1.913E+00	261.93
1.500	-1.032E+01	2.146E+00	-1.017E+02	164.89	0.	-3.081E-01	-1.884E+00	1.909E+00	260.71
1.520	-9.261E+00	1.969E+00	-9.241E+01	163.14	0.	-3.439E-01	-1.874E+00	1.905E+00	259.60
1.540	-8.285E+00	1.810E+00	-8.413E+01	161.55	0.	-3.766E-01	-1.863E+00	1.901E+00	258.57

TIME	APPLIED ACCEL AY	APPLIED ACCEL AZ	SURFACE ACO	SURFACE CCO	SURFACE RHO	TANGENT J	TANGENT K	NORMAL J	NORMAL K
1.300	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.217E+00	-.964	-.267	.267	-.964
1.320	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.192E+00	-.981	-.193	.193	-.981
1.340	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.177E+00	-.992	-.123	.123	-.992
1.360	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.169E+00	-.998	-.058	.058	-.998
1.380	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.166E+00	-1.000	.002	-.002	-1.000
1.400	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.169E+00	-.998	.057	-.057	-.998
1.420	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.174E+00	-.994	.106	-.106	-.994
1.440	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.182E+00	-.988	.151	-.151	-.988
1.460	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.192E+00	-.981	.192	-.192	-.981
1.480	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.203E+00	-.974	.228	-.228	-.974
1.500	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.215E+00	-.965	.261	-.261	-.965
1.520	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.227E+00	-.957	.290	-.290	-.957
1.540	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.239E+00	-.949	.316	-.316	-.949

TIME	FLUID FORCES ON TANK FY	FZ	MX	KEYS KEY1	KEY2	QUADRANTS NQB	NQF
1.300	8.5831E-02	1.4583E-01	-9.6402E-04	0	0	3	4
1.320	8.1856E-02	1.6796E-01	-3.9560E-03	0	0	3	4
1.340	8.1322E-02	1.8798E-01	-4.3868E-03	0	0	3	4
1.360	8.3398E-02	2.0547E-01	-2.8298E-03	0	0	3	4
1.380	8.7292E-02	2.2023E-01	1.2194E-04	0	0	2	3
1.400	9.2328E-02	2.3254E-01	3.9395E-03	0	0	2	3
1.420	9.7974E-02	2.4245E-01	8.1986E-03	0	0	2	3
1.440	1.0384E-01	2.5032E-01	1.2586E-02	0	0	2	3
1.460	1.0965E-01	2.5646E-01	1.6889E-02	0	0	2	3
1.480	1.1523E-01	2.6117E-01	2.0974E-02	0	0	2	3
1.500	1.2049E-01	2.6472E-01	2.4766E-02	0	0	2	3
1.520	1.2537E-01	2.6733E-01	2.8235E-02	0	0	2	3
1.540	1.2985E-01	2.6921E-01	3.1373E-02	0	0	2	3

18.05.35 CLOCK TIME
166.719 SEC. CPTIME
42 SEC. PPTIME

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

ORIGINAL PAGE IS OF POOR QUALITY

ANALYTICAL RESULTS

SYSTEM STATE

TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
1.560	-7.390E+00	1.668E+00	-7.678E+01	160.10	0.	-4.064E-01	-1.853E+00	1.897E+00	257.63
1.580	-6.568E+00	1.542E+00	-7.130E+01	158.77	0.	-4.336E-01	-1.843E+00	1.893E+00	256.76
1.600	-5.812E+00	1.430E+00	-6.459E+01	157.56	0.	-4.586E-01	-1.833E+00	1.889E+00	255.95
1.620	-5.112E+00	1.331E+00	-5.958E+01	156.44	0.	-4.817E-01	-1.823E+00	1.885E+00	255.20
1.640	-4.464E+00	1.245E+00	-5.523E+01	155.40	0.	-5.030E-01	-1.813E+00	1.882E+00	254.50
1.660	-3.861E+00	1.169E+00	-5.145E+01	154.44	0.	-5.228E-01	-1.804E+00	1.878E+00	253.84
1.680	-3.296E+00	1.105E+00	-4.821E+01	153.54	0.	-5.413E-01	-1.795E+00	1.875E+00	253.22
1.700	-2.765E+00	1.050E+00	-4.546E+01	152.70	0.	-5.587E-01	-1.786E+00	1.872E+00	252.63
1.720	-2.261E+00	1.004E+00	-4.316E+01	151.90	0.	-5.752E-01	-1.778E+00	1.868E+00	252.07
1.740	-1.781E+00	9.675E-01	-4.128E+01	151.13	0.	-5.908E-01	-1.769E+00	1.865E+00	251.53
1.760	-1.320E+00	9.394E-01	-3.979E+01	150.40	0.	-6.059E-01	-1.761E+00	1.862E+00	251.01
1.780	-8.740E-01	9.194E-01	-3.867E+01	149.70	0.	-6.205E-01	-1.752E+00	1.859E+00	250.50
1.800	-4.384E-01	9.074E-01	-3.790E+01	149.01	0.	-6.347E-01	-1.744E+00	1.856E+00	250.00

	APPLIED ACCEL		SURFACE			TANGENT		NORMAL	
TIME	AY	AZ	ACO	CCO	RHO	J	K	J	K
1.560	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.251E+00	-.940	.340	-.340	-.940
1.580	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.263E+00	-.932	.362	-.362	-.932
1.600	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.275E+00	-.924	.382	-.382	-.924
1.620	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.286E+00	-.917	.400	-.400	-.917
1.640	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.297E+00	-.909	.416	-.416	-.909
1.660	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.308E+00	-.902	.431	-.431	-.902
1.680	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.318E+00	-.895	.446	-.446	-.895
1.700	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.328E+00	-.889	.459	-.459	-.889
1.720	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.338E+00	-.882	.471	-.471	-.882
1.740	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.348E+00	-.876	.483	-.483	-.876
1.760	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.357E+00	-.870	.494	-.494	-.870
1.780	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.367E+00	-.863	.505	-.505	-.863
1.800	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.376E+00	-.857	.515	-.515	-.857

	FLUID FORCES ON TANK			KEYS		QUADRANTS	
TIME	FY	FZ	MX	KEY1	KEY2	NQB	NQF
1.560	1.3396E-01	2.7049E-01	3.4195E-02	0	0	2	3
1.580	1.3769E-01	2.7132E-01	3.6721E-02	0	0	2	3
1.600	1.4109E-01	2.7179E-01	3.8978E-02	0	0	2	3
1.620	1.4419E-01	2.7197E-01	4.0994E-02	0	0	2	3
1.640	1.4701E-01	2.7194E-01	4.2796E-02	0	0	2	3
1.660	1.4959E-01	2.7173E-01	4.4411E-02	0	0	2	3
1.680	1.5196E-01	2.7139E-01	4.5863E-02	0	0	2	3
1.700	1.5414E-01	2.7094E-01	4.7173E-02	0	0	2	3
1.720	1.5616E-01	2.7040E-01	4.8360E-02	0	0	2	3
1.740	1.5804E-01	2.6978E-01	4.9442E-02	0	0	2	3
1.760	1.5981E-01	2.6910E-01	5.0432E-02	0	0	2	3
1.780	1.6148E-01	2.6835E-01	5.1344E-02	0	0	2	3
1.800	1.6306E-01	2.6755E-01	5.2188E-02	0	0	2	3

CHECK OUT OF PROGRAM LAMPS USING TEST 16
FC43 FLUID

18.05.39 CLOCK TIME
167.172 SEC. CPTIME
43 SEC. PPTIME

A N A L Y T I C A L   R E S U L T S

****SYSTEM STATE****

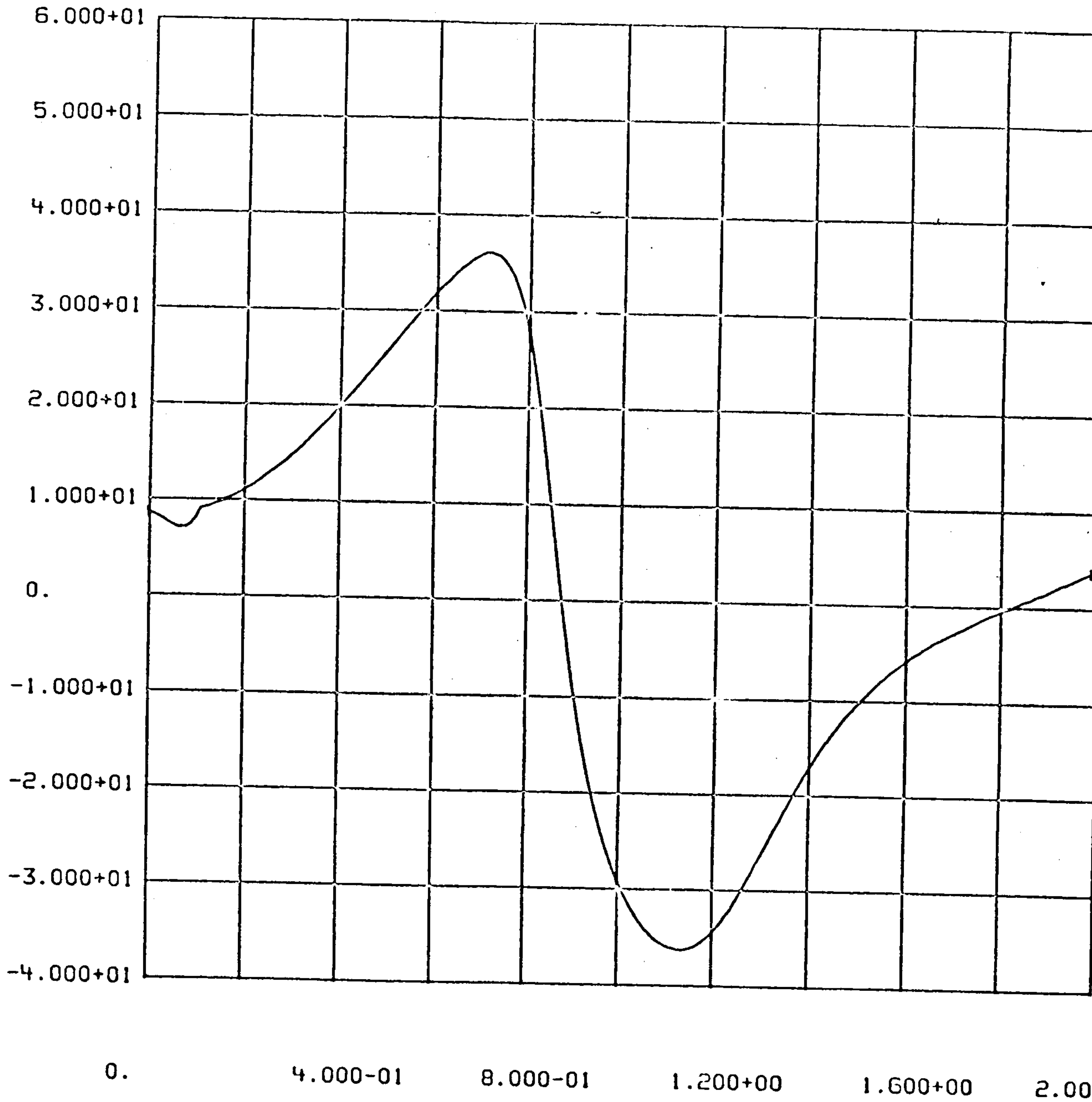
TIME	VTDOT	VT	BETADOT	BETA	X	Y	Z	R	PHI
1.820	-9.625E-03	9.031E-01	-3.747E+01	148.33	0.	-6.486E-01	-1.735E+00	1.853E+00	249.50
1.840	4.159E-01	9.066E-01	-3.735E+01	147.65	0.	-6.625E-01	-1.727E+00	1.849E+00	249.01
1.860	8.417E-01	9.178E-01	-3.754E+01	146.98	0.	-6.764E-01	-1.718E+00	1.846E+00	248.51
1.880	1.271E+00	9.366E-01	-3.804E+01	146.30	0.	-6.904E-01	-1.709E+00	1.843E+00	248.00
1.900	1.708E+00	9.633E-01	-3.883E+01	145.61	0.	-7.046E-01	-1.699E+00	1.839E+00	247.47
1.920	2.155E+00	9.980E-01	-3.992E+01	144.90	0.	-7.192E-01	-1.689E+00	1.836E+00	246.93
1.940	2.615E+00	1.041E+00	-4.130E+01	144.17	0.	-7.342E-01	-1.678E+00	1.832E+00	246.37
1.960	3.092E+00	1.092E+00	-4.297E+01	143.41	0.	-7.497E-01	-1.667E+00	1.828E+00	245.78
1.980	3.590E+00	1.152E+00	-4.493E+01	142.62	0.	-7.659E-01	-1.655E+00	1.823E+00	245.16
2.000	4.110E+00	1.221E+00	-4.718E+01	141.79	0.	-7.829E-01	-1.641E+00	1.819E+00	244.50

TIME	****APPLIED ACCEL**** AY	AZ	****SURFACE**** ACO	CCO	RHO	****TANGENT**** J	K	****NORMAL**** J	K
1.820	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.386E+00	-.851	.525	-.525	-.851
1.840	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.396E+00	-.845	.535	-.535	-.845
1.860	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.406E+00	-.838	.545	-.545	-.838
1.880	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.416E+00	-.832	.555	-.555	-.832
1.900	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.427E+00	-.825	.565	-.565	-.825
1.920	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.438E+00	-.818	.575	-.575	-.818
1.940	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.450E+00	-.811	.585	-.585	-.811
1.960	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.463E+00	-.803	.596	-.596	-.803
1.980	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.476E+00	-.795	.607	-.607	-.795
2.000	-1.900E+01	-3.078E+01	4.454E-01	2.698E-01	1.490E+00	-.786	.619	-.619	-.786

TIME	****FLUID FORCES ON TANK**** FY	FZ	MX	****KEYS**** KEY1	KEY2	*QUADRANTS* NQB	NQF
1.820	1.6458E-01	2.6668E-01	5.2972E-02	0	0	2	3
1.840	1.6605E-01	2.6575E-01	5.3705E-02	0	0	2	3
1.860	1.6747E-01	2.6475E-01	5.4390E-02	0	0	2	3
1.880	1.6886E-01	2.6368E-01	5.5032E-02	0	0	2	3
1.900	1.7022E-01	2.6252E-01	5.5633E-02	0	0	2	3
1.920	1.7155E-01	2.6125E-01	5.6192E-02	0	0	2	3
1.940	1.7287E-01	2.5988E-01	5.6709E-02	0	0	2	3
1.960	1.7417E-01	2.5838E-01	5.7180E-02	0	0	2	3
1.980	1.7546E-01	2.5674E-01	5.7597E-02	0	0	2	3
2.000	1.7672E-01	2.5494E-01	5.7954E-02	0	0	2	3

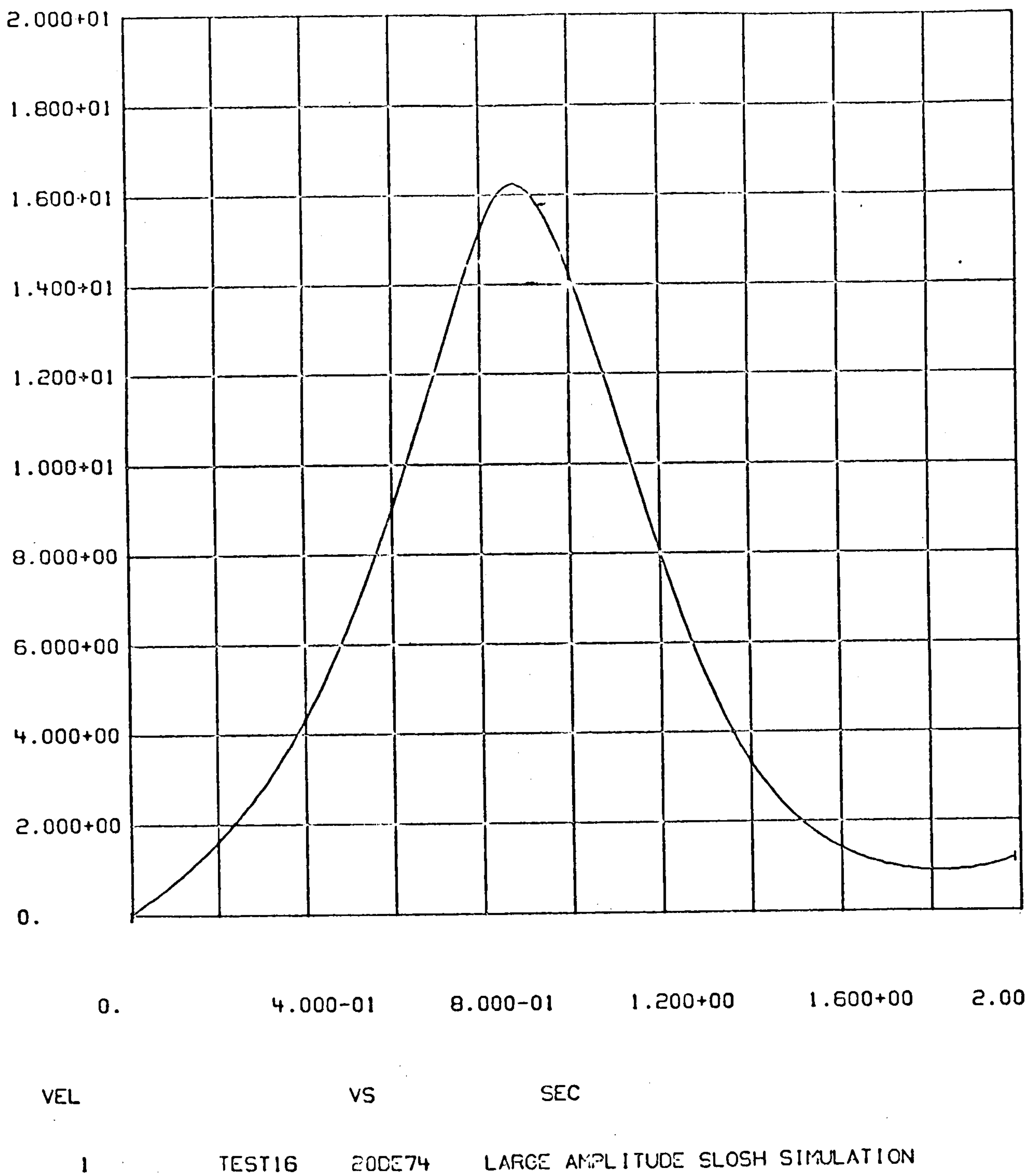
```
RUN NO. TEST16                        DATE 03FE75                         PAGE NO.    18
                                     RUN BY RL BERRY
                                                                  18.05.43 CLOCK  TIME
     CHECK CUT OF PROGRAM LAMPS USING TEST 16                    167.515 SEC. CPTIME
     FC43 FLUID                                                    44     SEC. PPTIME


                         **********************************
                         **LAMPS SUCCESSFULLY TERMINATED**
                         **********************************
```

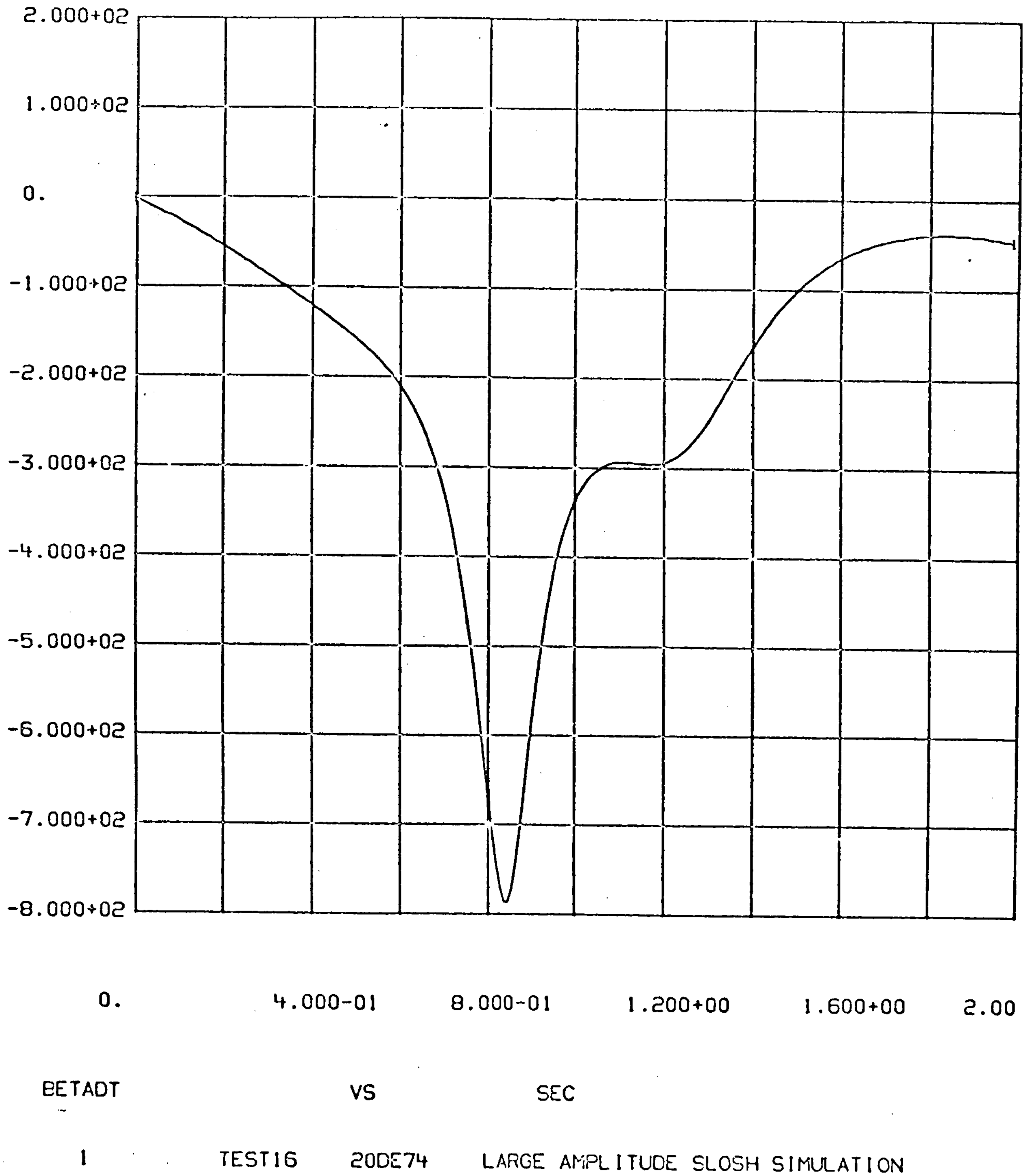
SAMPLE PLOTS

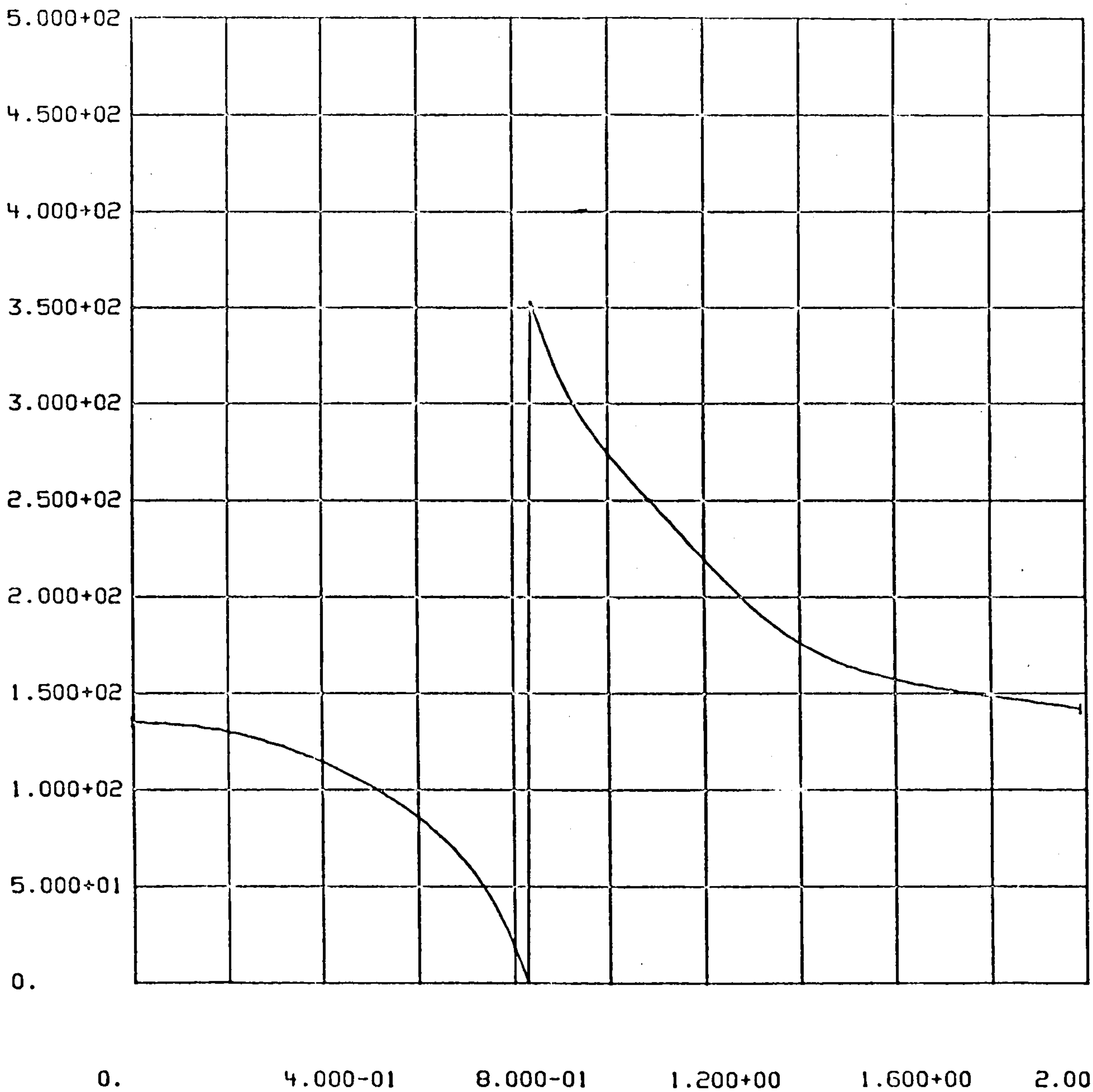


ACCEL VS SEC

1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION

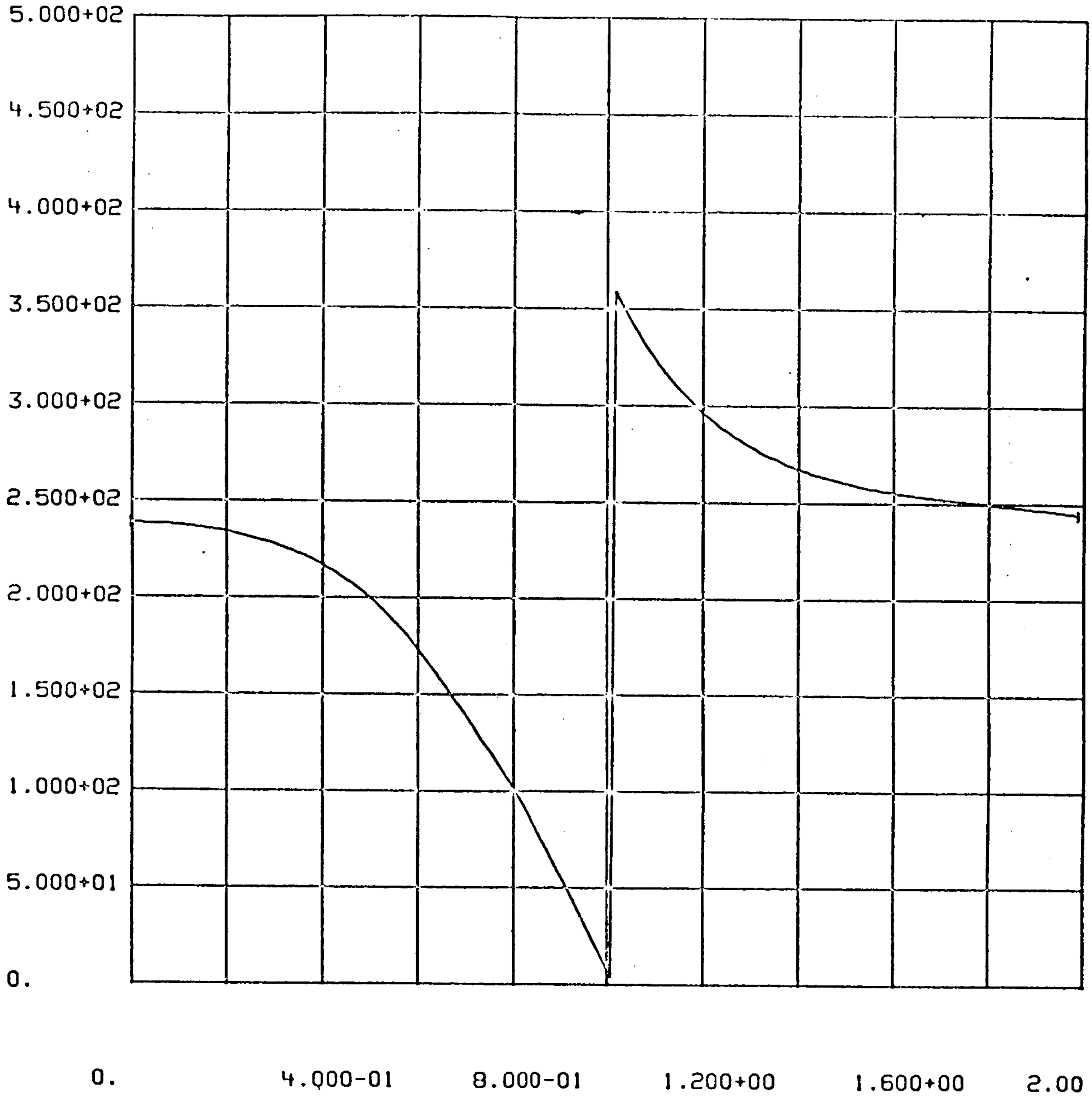

2.000+01
1.800+01
1.600+01
1.400+01
1.200+01
1.000+01
8.000+00
6.000+00
4.000+00
2.000+00
0.
0.
4.000-01
8.000-01
1.200+00
1.600+00
2.00
VEL
VS
SEC
1
TEST16
20DE74
LARGE AMPLITUDE SLOSH SIMULATION


2.000+02
1.000+02
0.
-1.000+02
-2.000+02
-3.000+02
-4.000+02
-5.000+02
-6.000+02
-7.000+02
-8.000+02
0.
4.000-01
8.000-01
1.200+00
1.600+00
2.00
BETADT VS SEC
1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION



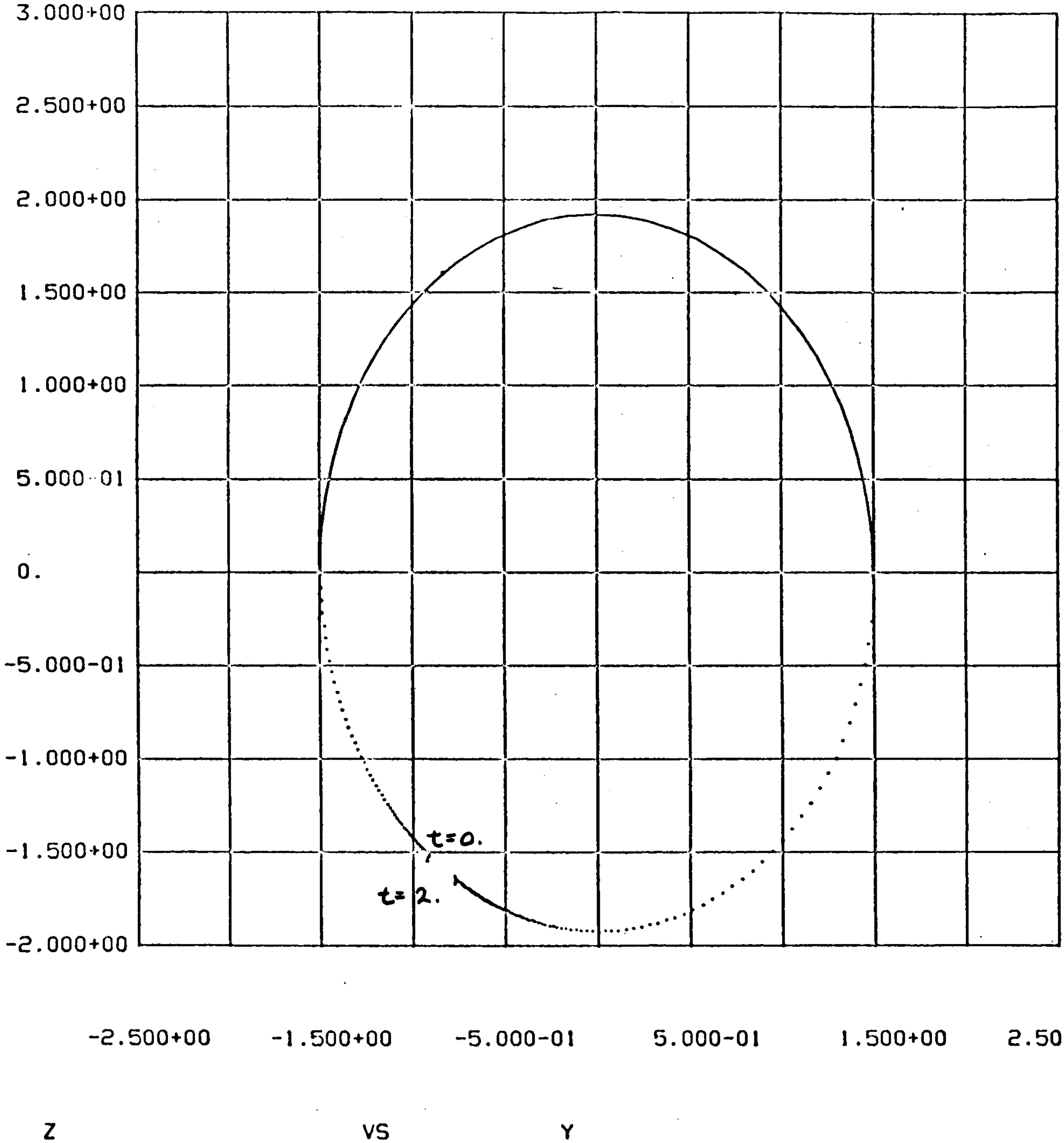
BETA VS SEC

1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION

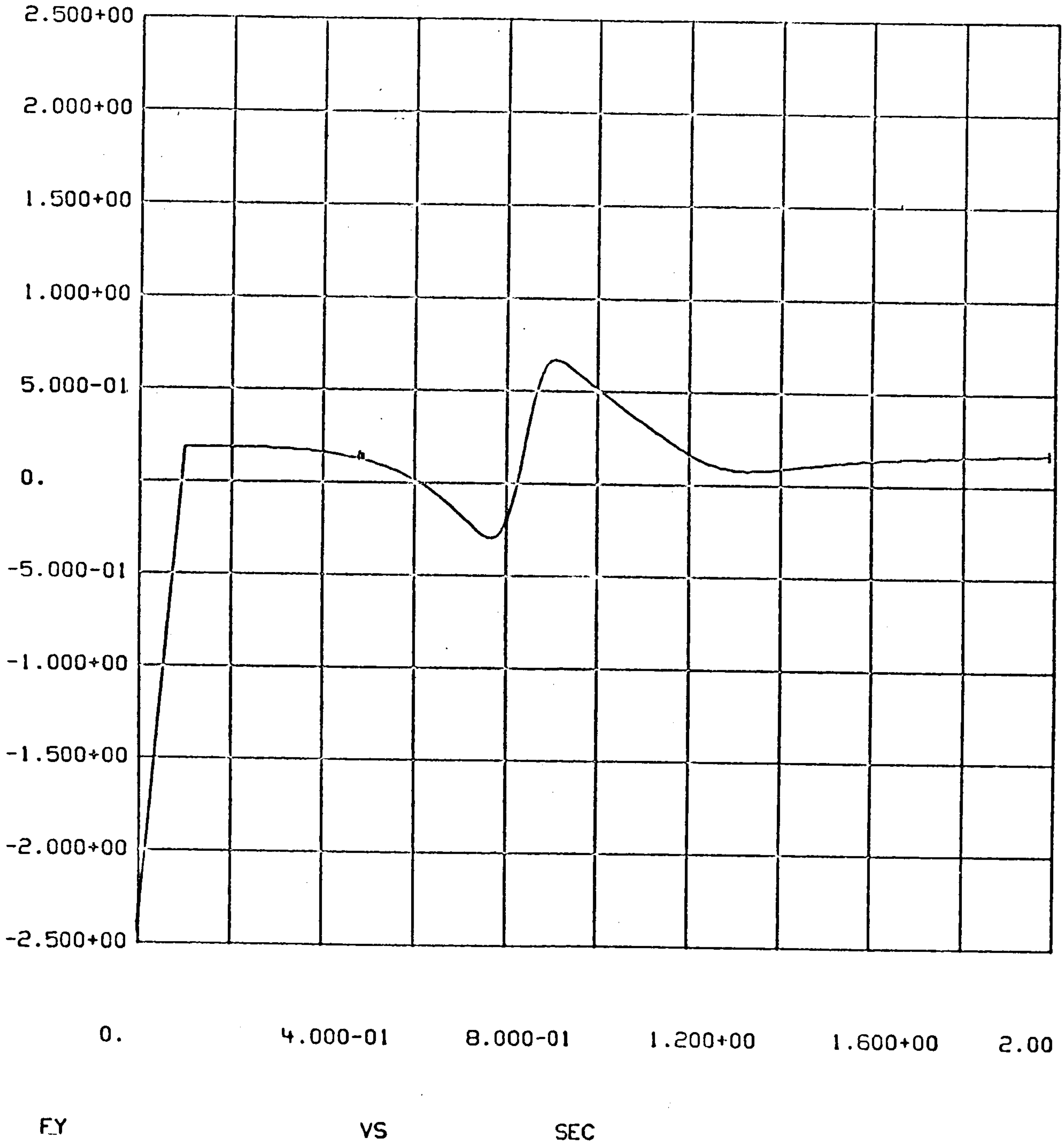


PHI VS SEC

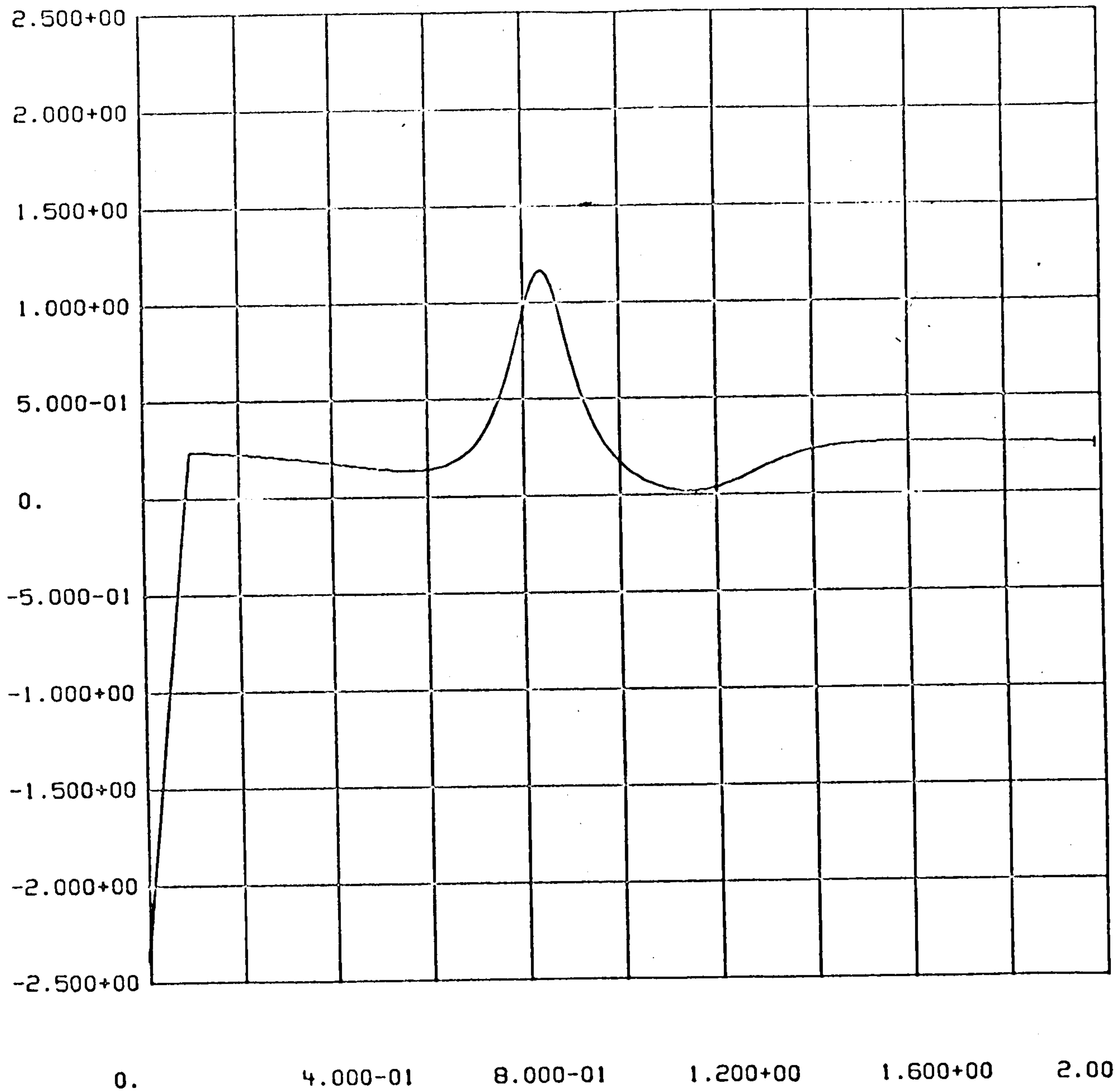
1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION



1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION

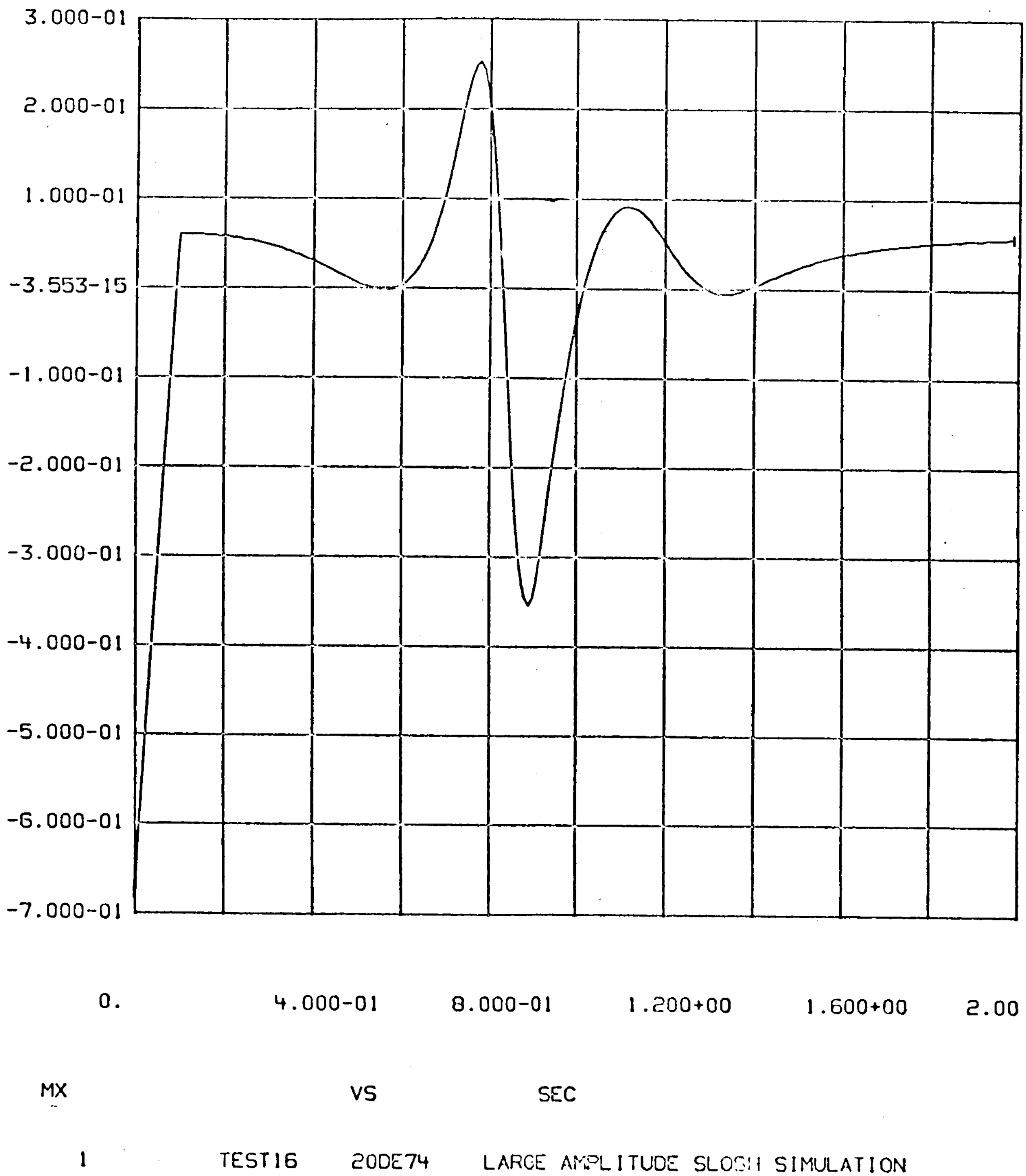


1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION



FZ VS SEC

1 TEST16 20DE74 LARGE AMPLITUDE SLOSH SIMULATION


3.000-01
2.000-01
1.000-01
-3.553-15
-1.000-01
-2.000-01
-3.000-01
-4.000-01
-5.000-01
-6.000-01
-7.000-01
0.
4.000-01
8.000-01
1.200+00
1.600+00
2.00
MX
VS
SEC
1
TEST16
20DE74
LARGE AMPLITUDE SLOSH SIMULATION

APPENDIX C - TEST AND ANALYTICAL RESULTS

This appendix presents (Figures C-1 through C-22) the reduced test data for all 22 test cases as well as the analytical prediction for each case assuming no viscous dissipative force ($\eta = 0, \mu = 0$). In general, an update criteria (CRIT) of 2% was used, however, some cases were run with a value of 0.5%. It has been found that smaller values of CRIT can drastically improve the quality of the analytical prediction for some test configurations. This improvement can be seen by comparing Figures C-17 and C-23. These figures both present data comparisons for test 17 (50% fill, 45° tank inclination). The analytic results shown in Figure C-23 were run with CRIT = 2%, while those in Figure C-17 were run with CRIT = 0.5%. The more lax update criteria (Figure C-23) allows excessive deviation from the constraint surface yielding more pronounced discontinuities at updates.

Table C-1 summarizes the test conditions for each case. Values of axial acceleration (AZI) were calculated based on test time, drop capsule and drag shield masses, and drop capsule travel distance. Lateral accelerations (AYI) were scaled from high speed photographs taken during the testing.

Table C-2 presents a qualitative evaluation of each test case including an assessment of the worth of the measured forces. Test eccentricities are also noted.

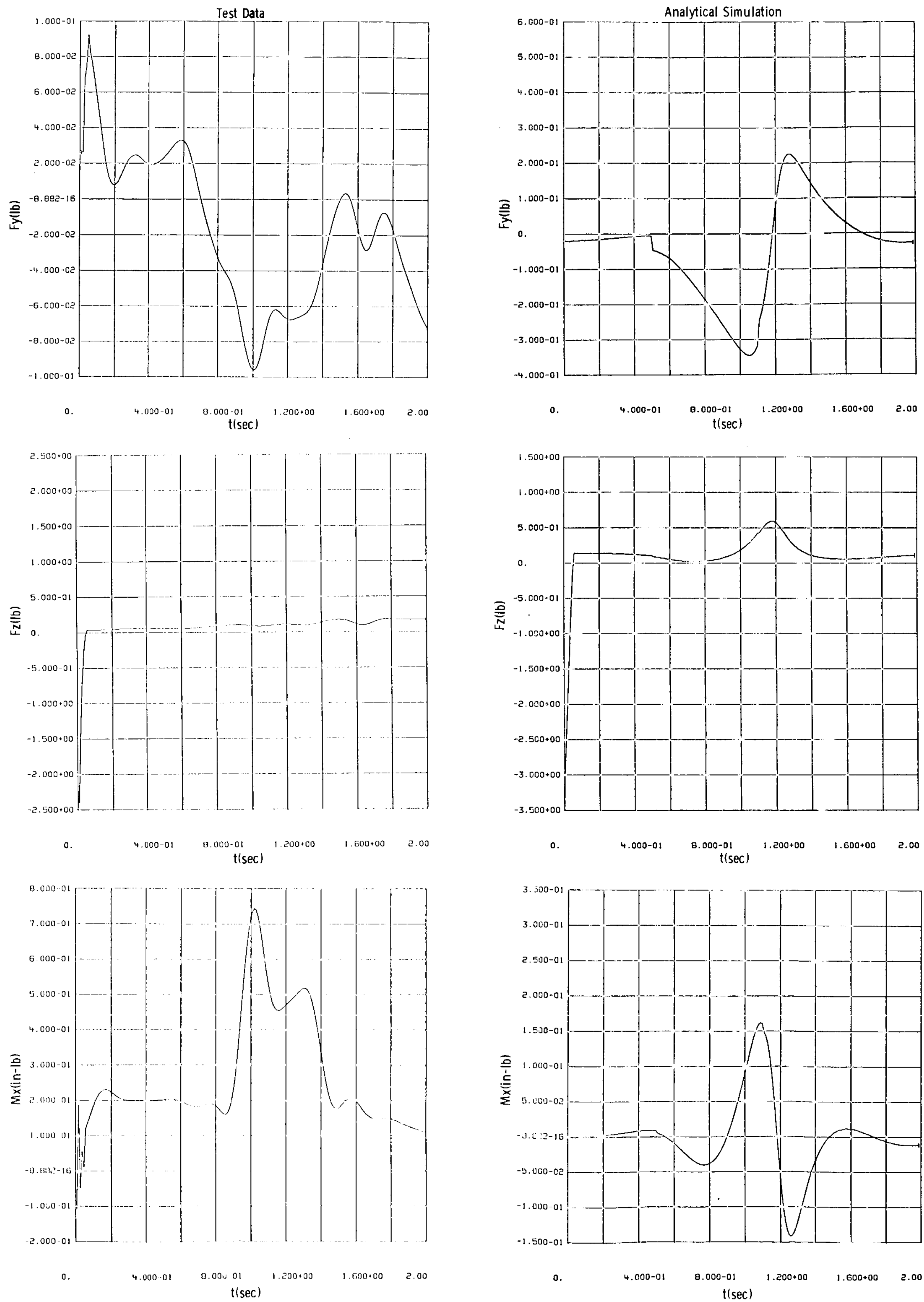


Figure C-1. Test 1; 25% Fill; θx = 0°; A_a = .045g; CRIT = 2.0%

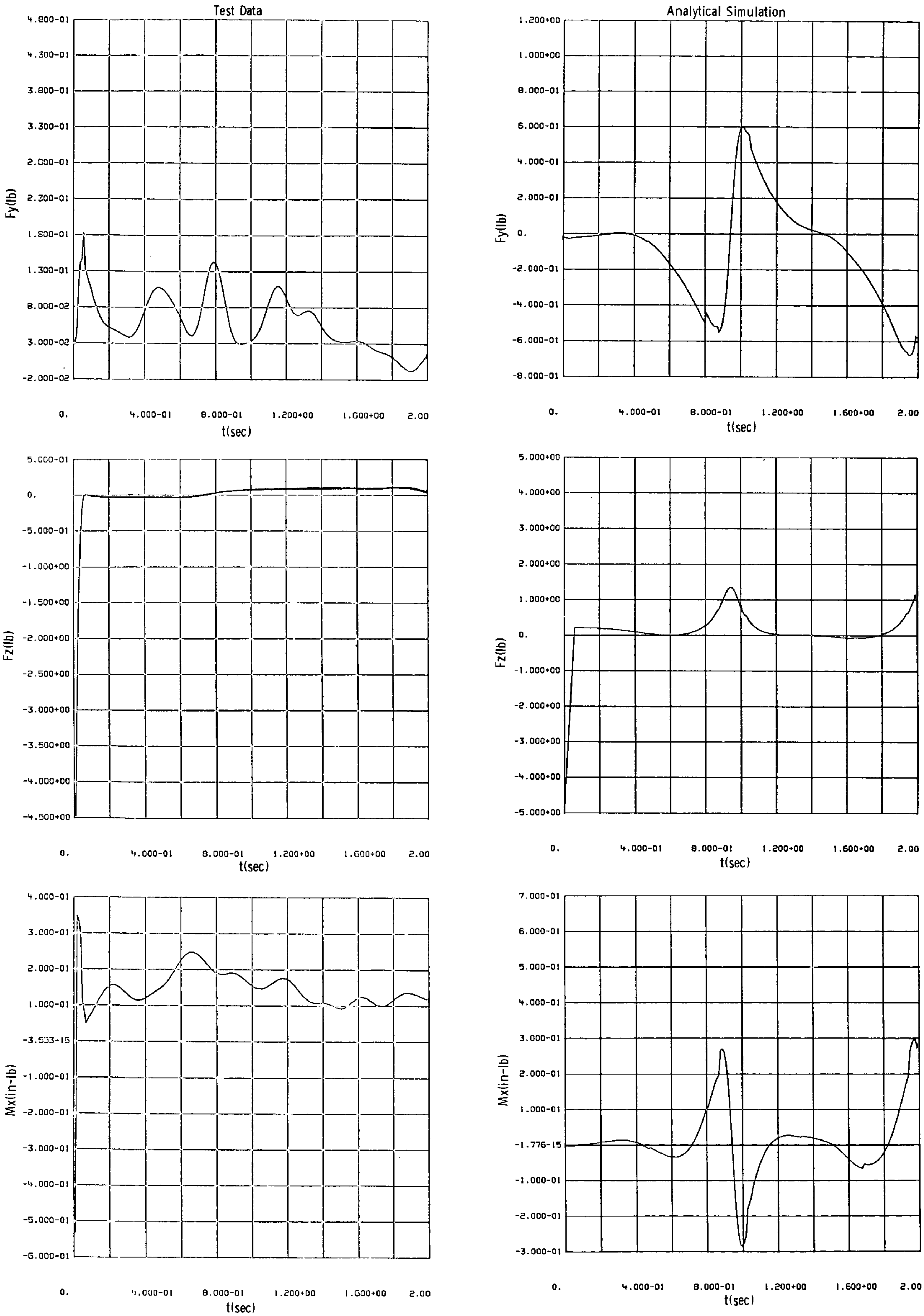


Figure C-2. Test 2; 50% Fill; $\theta x = 0°$; A_a = 045g; CRIT = 0.5%

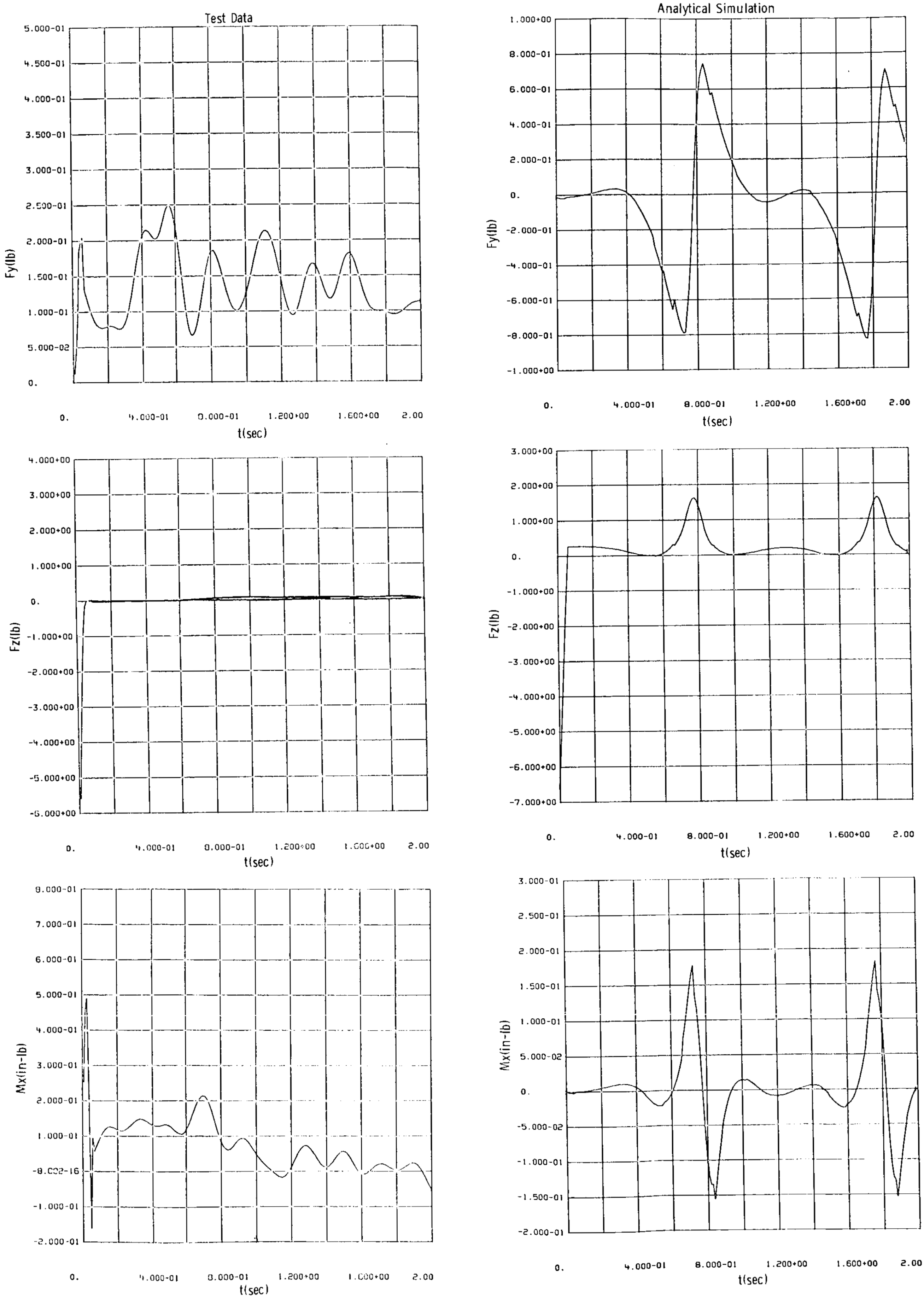


Figure C-3. Test 3; 75% Fill; $\theta x = 0^{\circ}$; $A_a = .045g$; CRIT = 0.5%

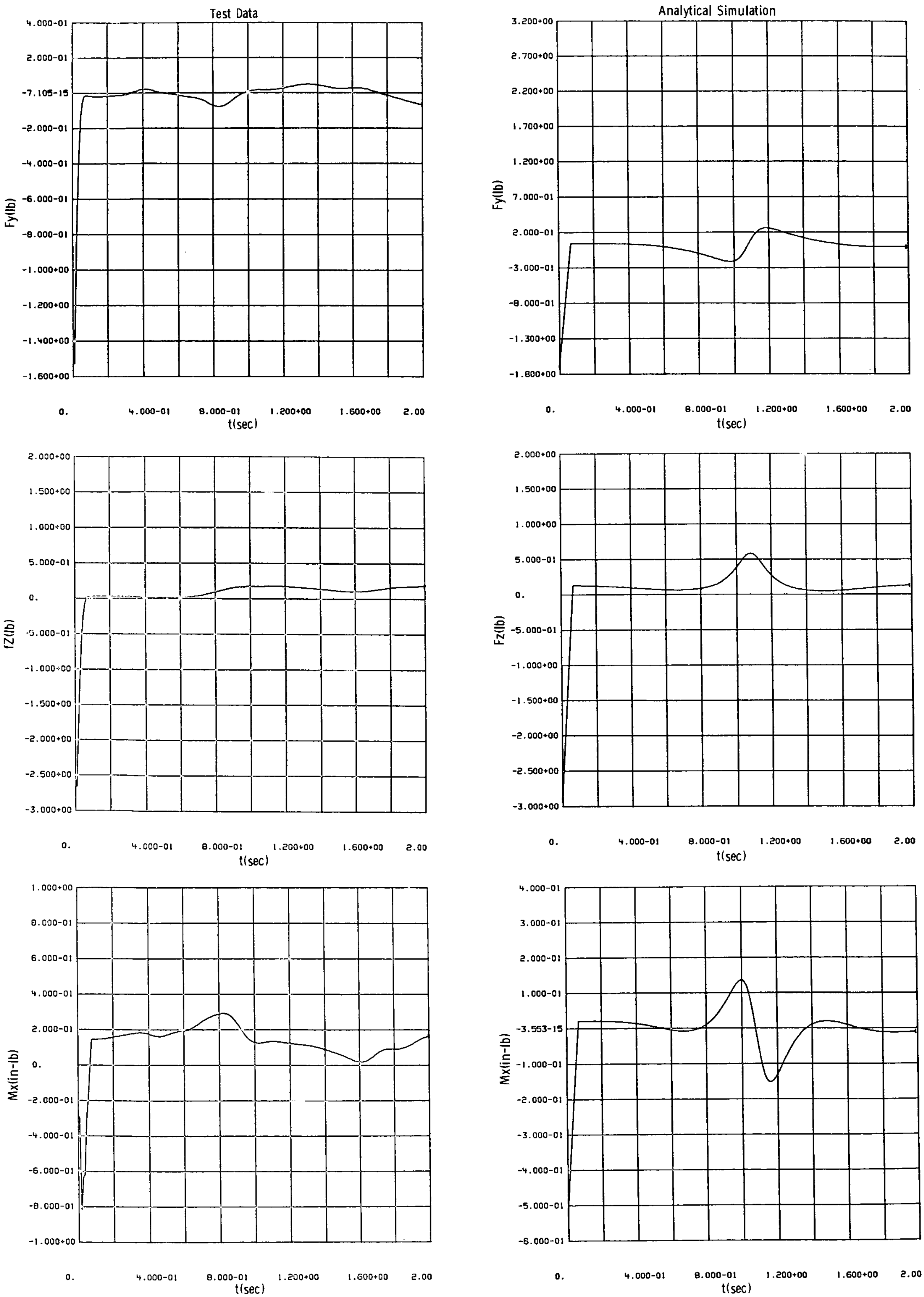


Figure C-4. Test 4; 25% Fill; $\theta x = 30^\circ$; $A_a = .045g$; CRIT = 2.0%

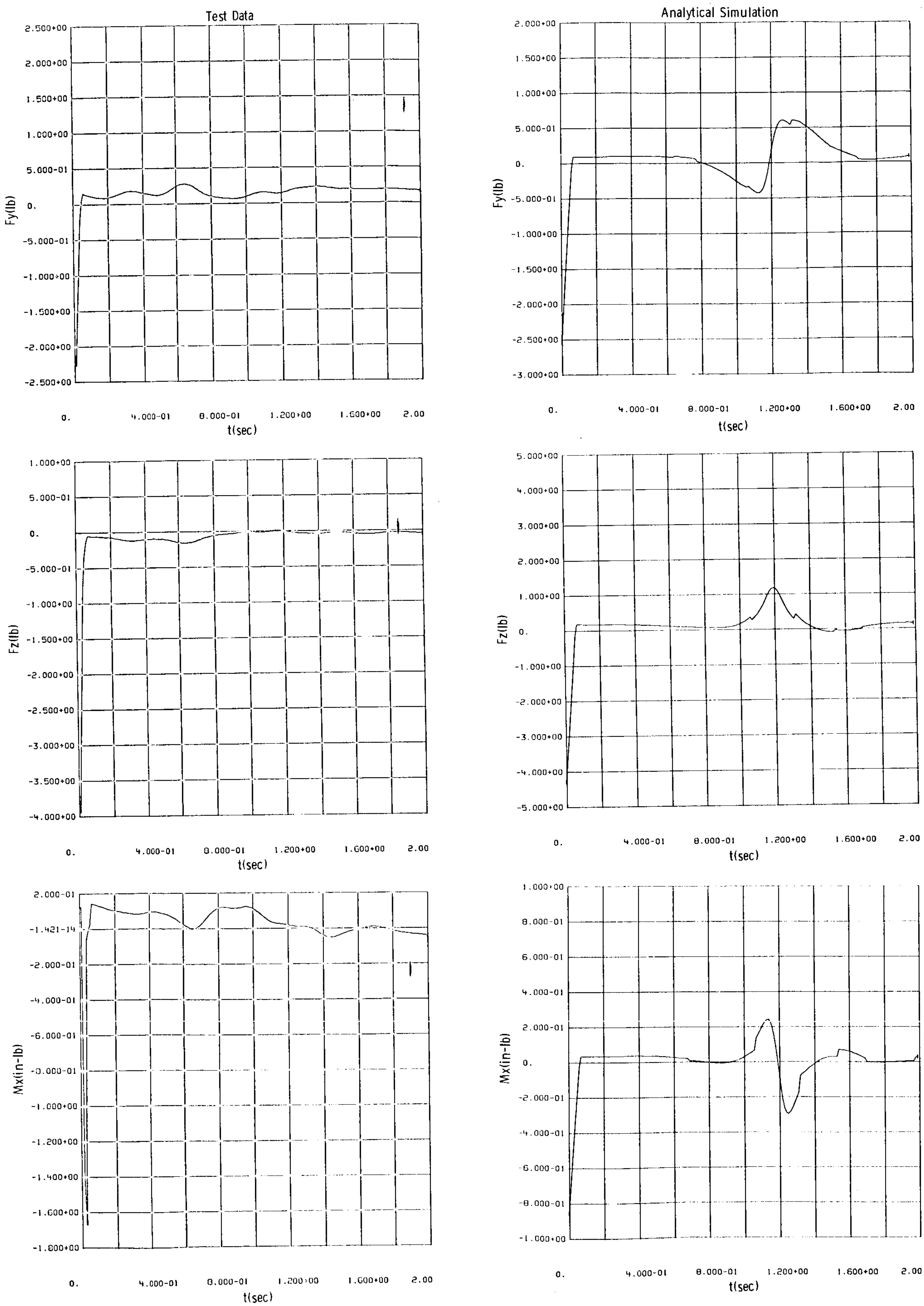


Figure C-5. Test 5; 50% Fill; θx = 30° A_a = .045g; CRIT = 2.0%

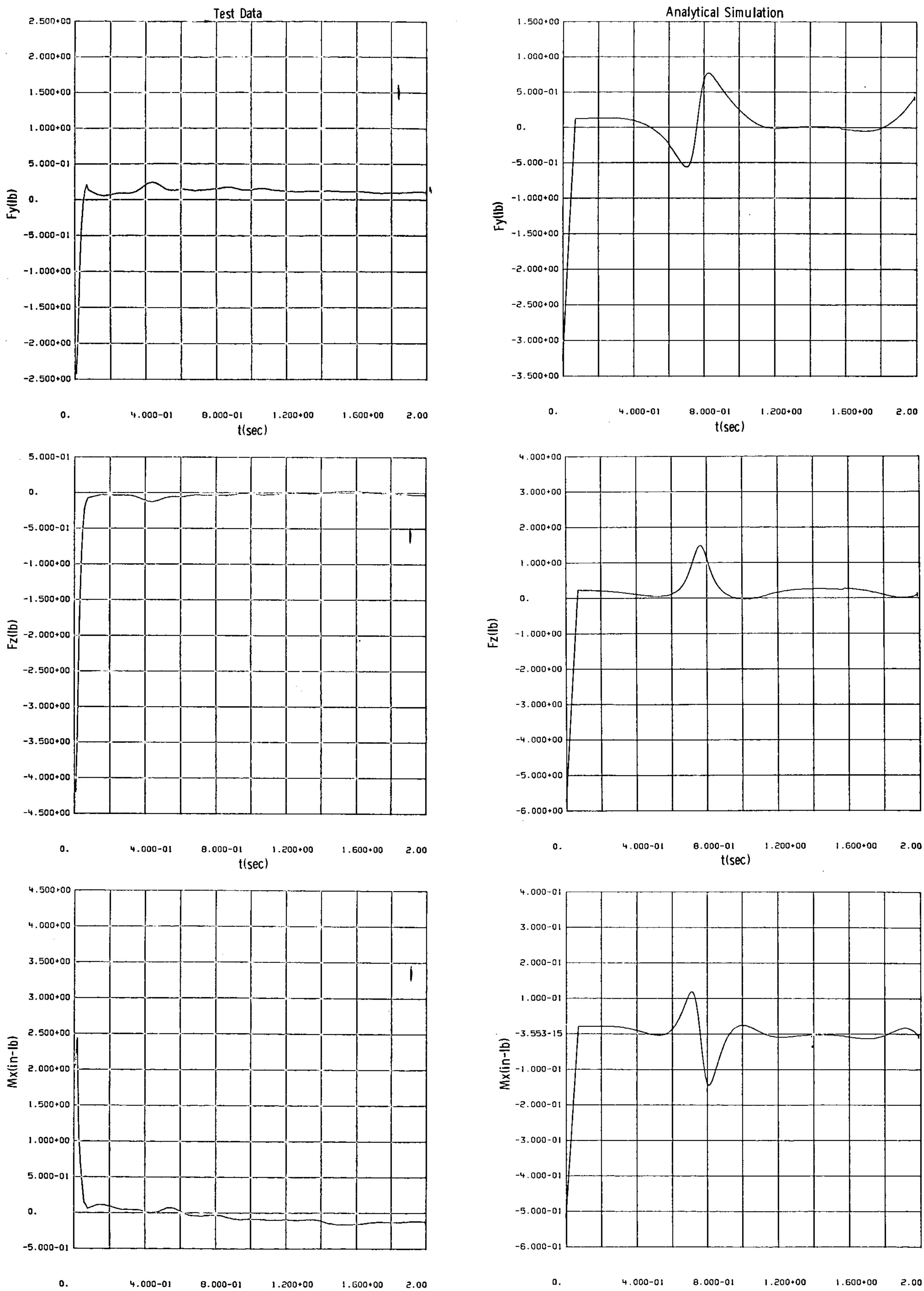


Figure C-6. Test 6; 75% Fill; $\epsilon x = 30^\circ$; $A_a = .045g$; CRIT = 2.0%

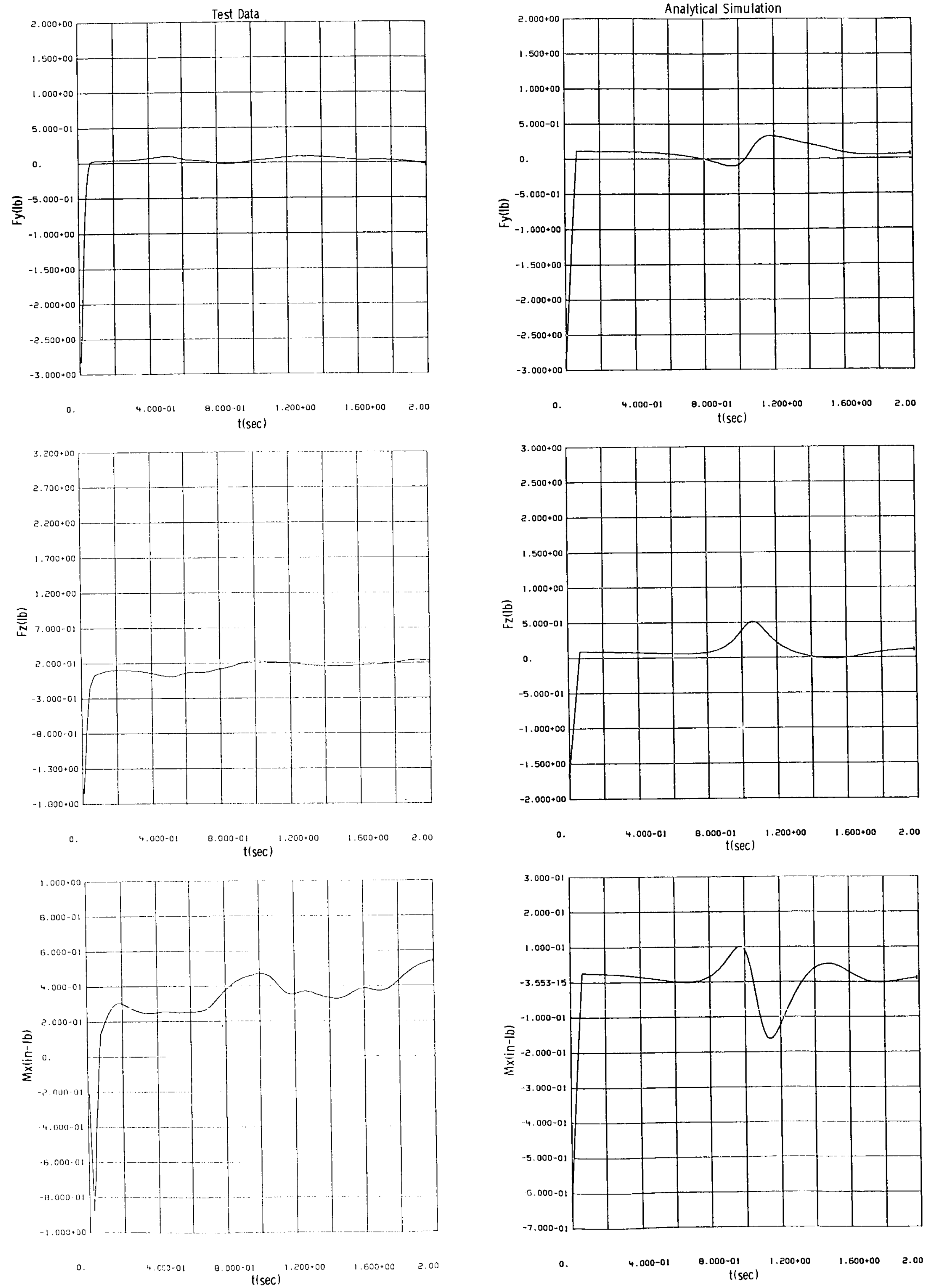


Figure C-7. Test 7; 25% Fill; $\theta x = 60°$; $A_a = .045g$; CRIT = 2.0%

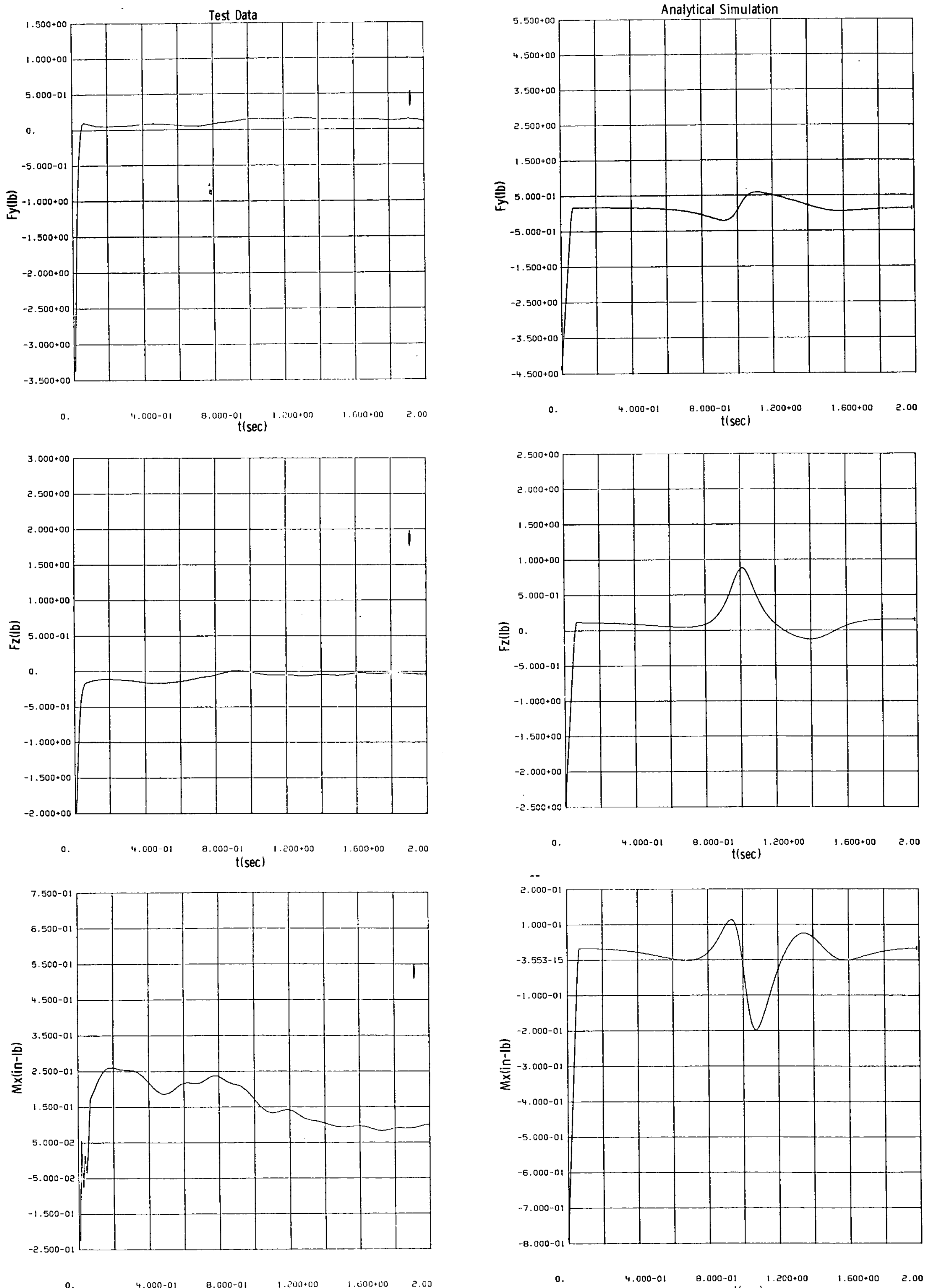


Figure C-8. Test 8; 50% Fill; $\theta x = 60^{\circ}$; $A_a = .045g$; CRIT = 2.0%

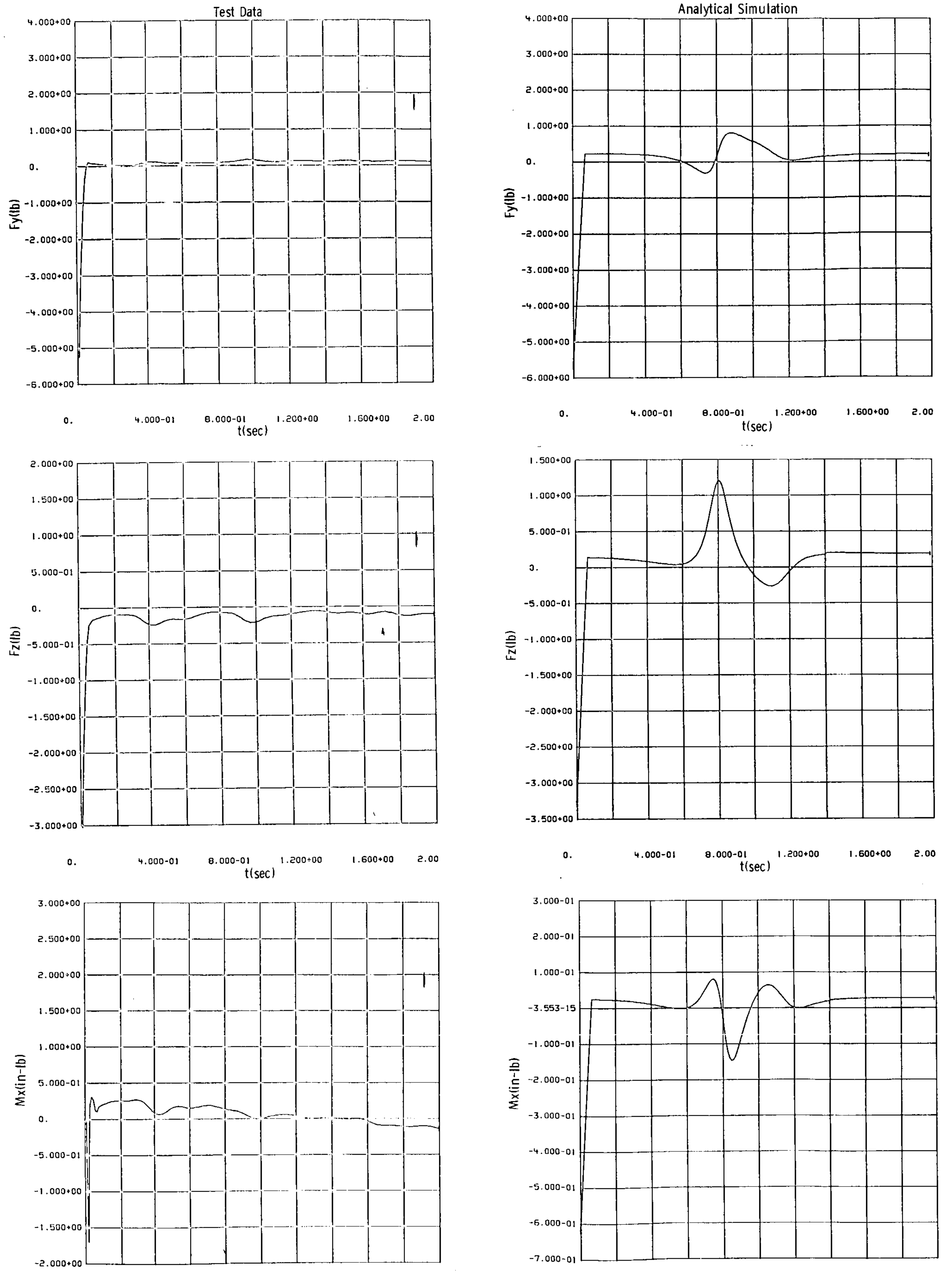


Figure C-9. Test 9; 75% Fill; $\theta x = 60^{\circ}$; $A_a = .045g$; CRIT = 2.0%

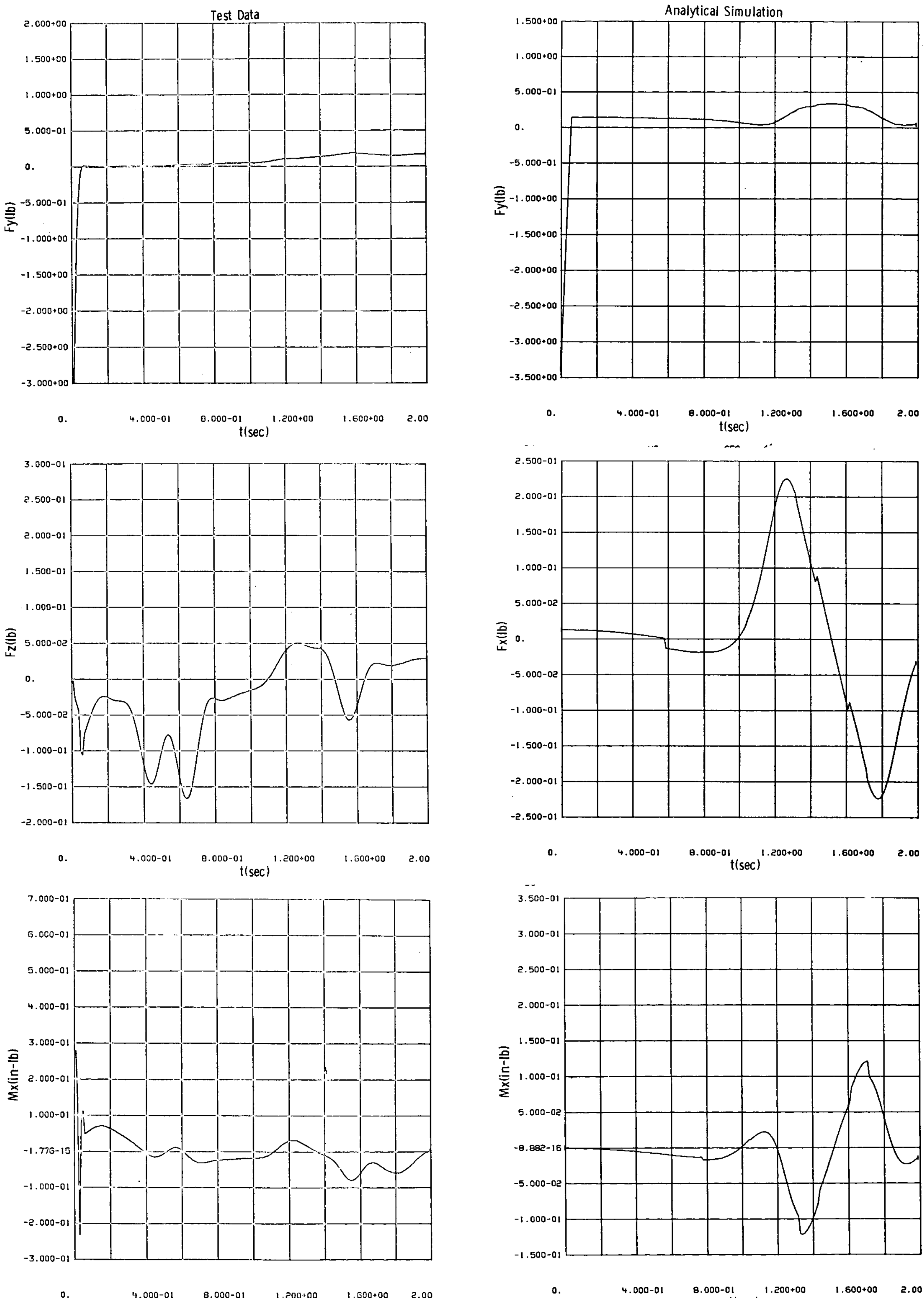


Figure C-10. Test 10; 25% Fill; $\theta x = 90^\circ$; $A_a = .045g$; CRIT = 0.5%

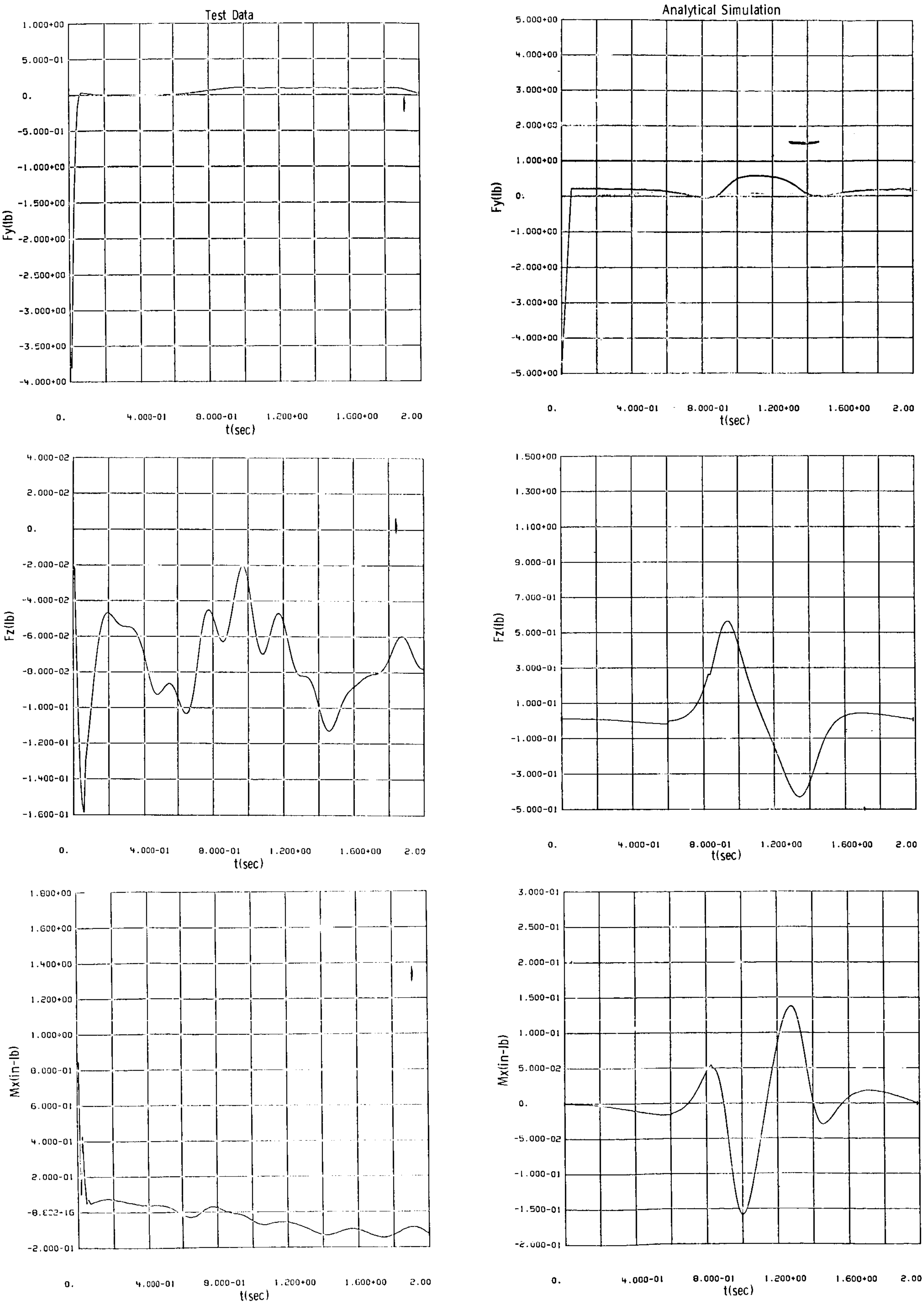


Figure C-11. Test 11; 50% Fill; θx = 90°; A_a = .045g; CRIT = 2.0%

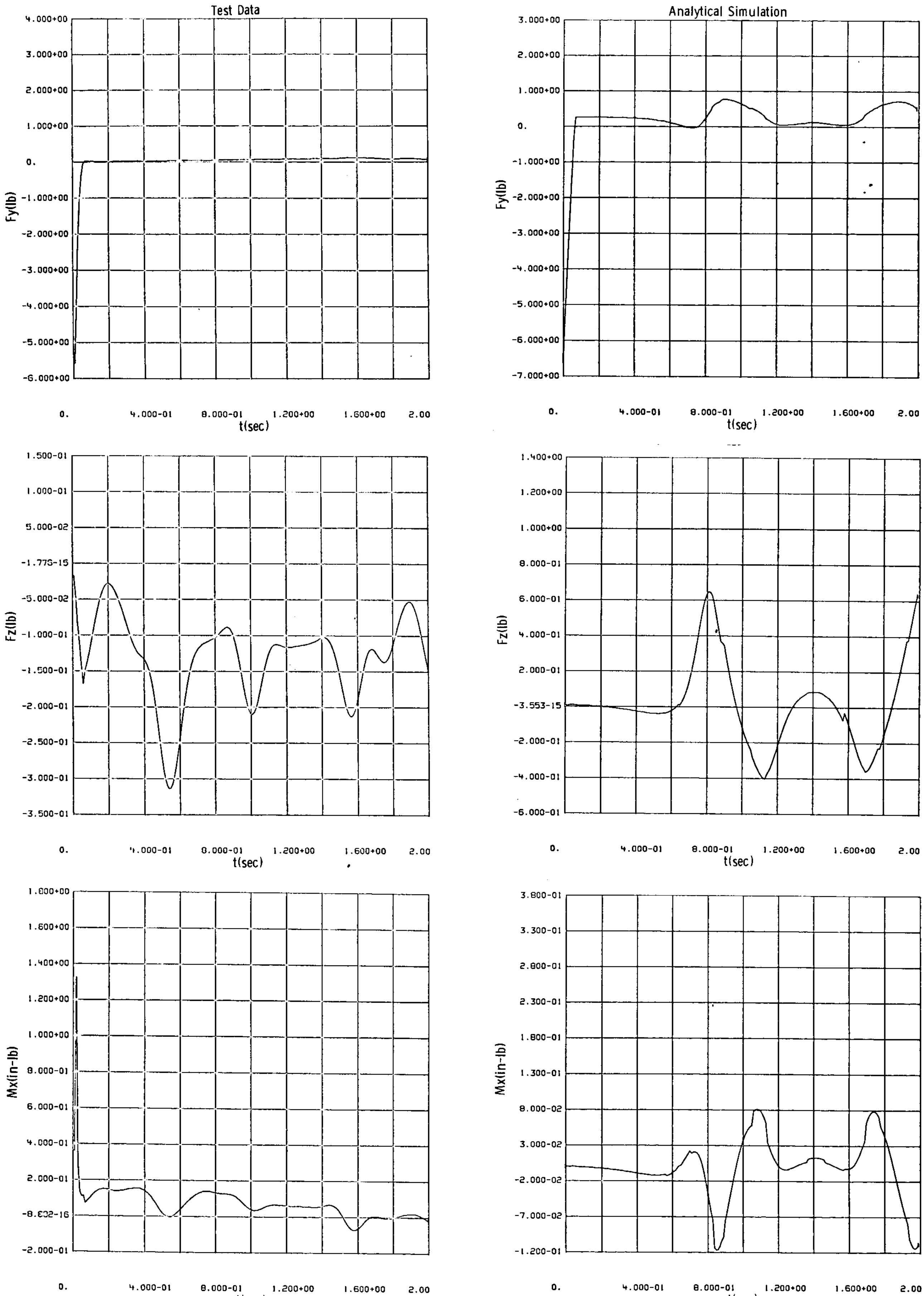


Figure C-12. Test 12; 75% Fill; $\theta X = 90^\circ$; $A_a = .045g$; CRIT = 0.5%

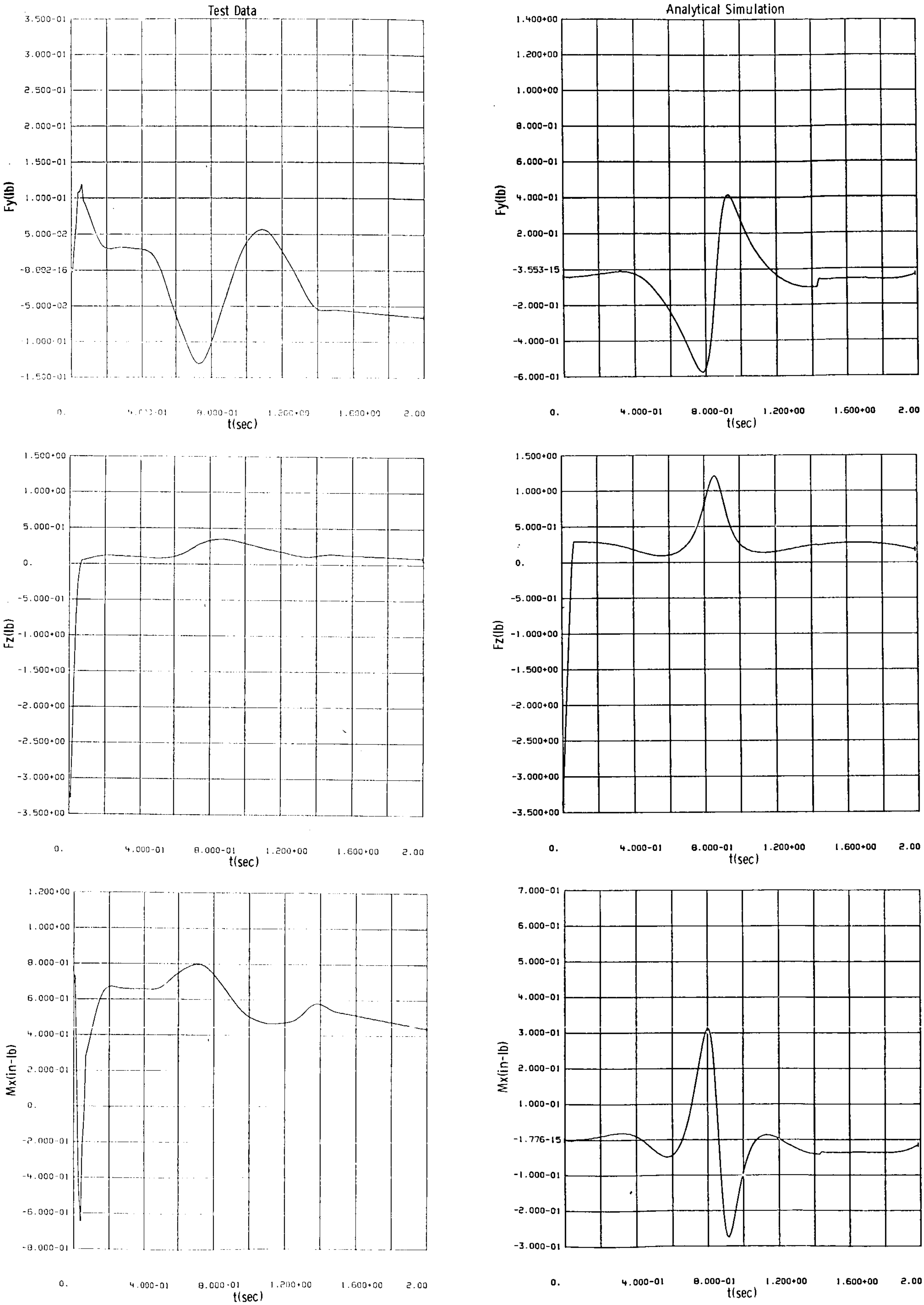


Figure C-13. Test 13; 25% Fill; θx = 0.0; A_a = .09g; CRIT = 2.0%

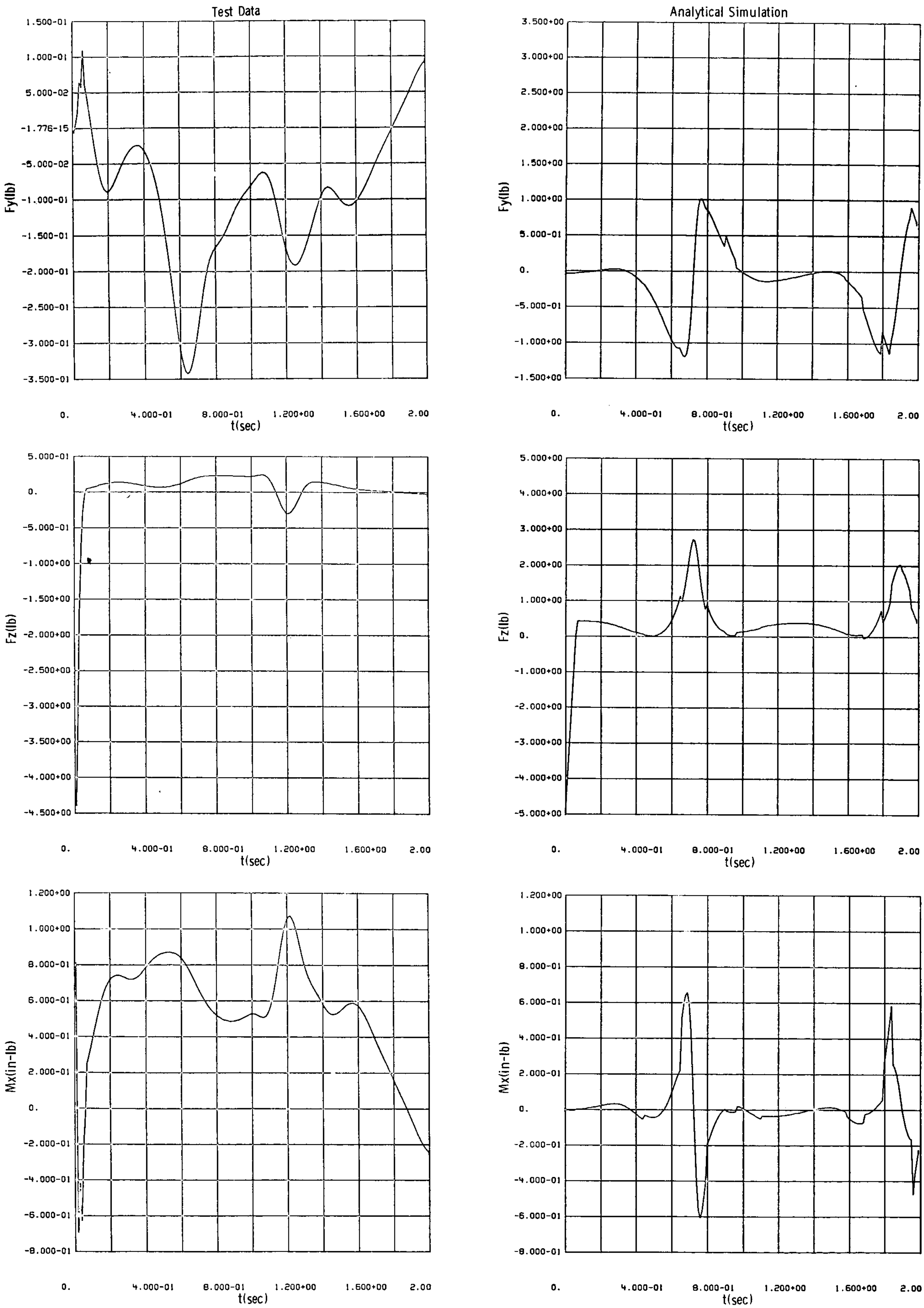


Figure C-14. Test 14; 50% Fill; $\theta x = 0°$; $A_a = .09g$; CRIT = 2.0%

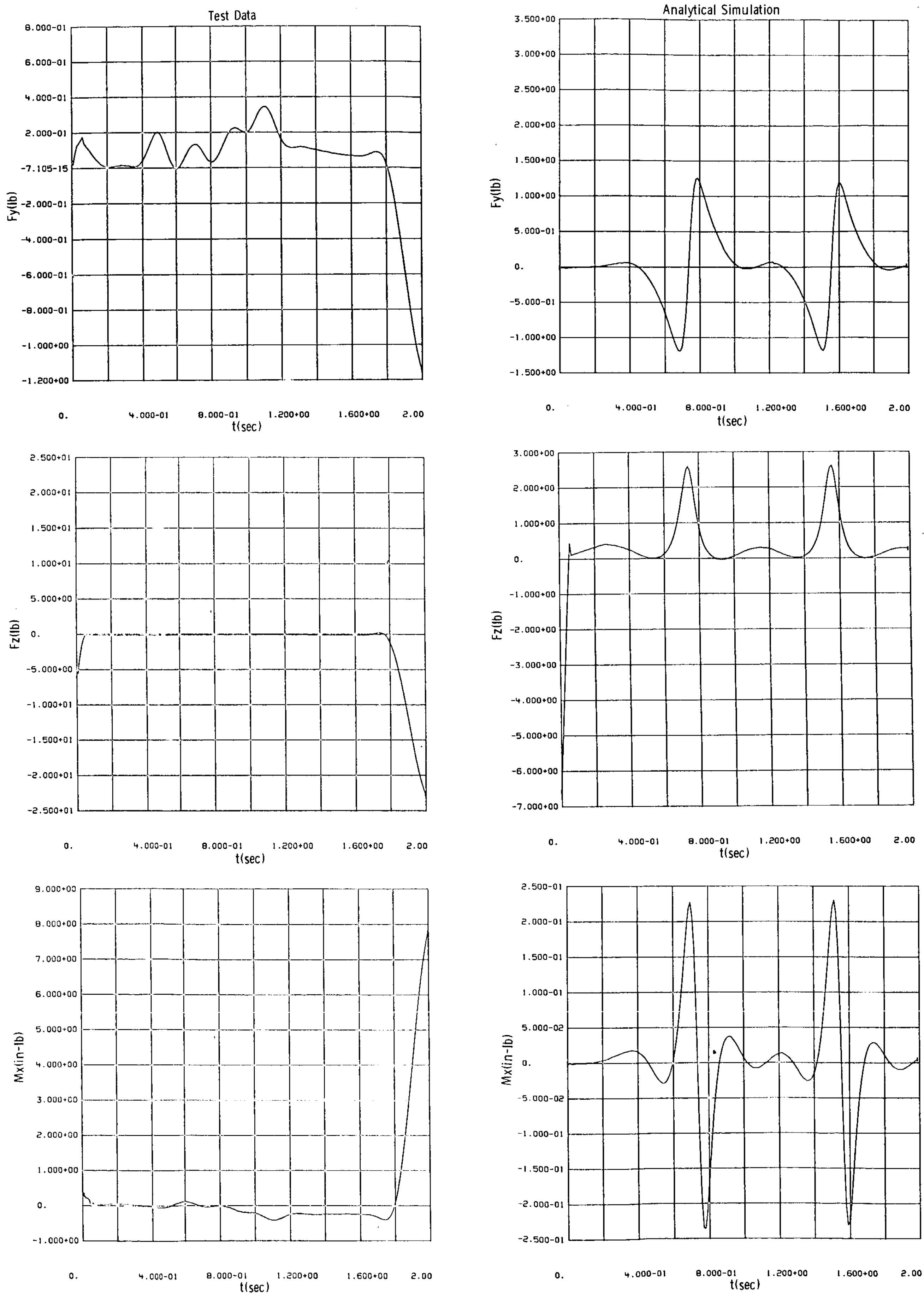


Figure C-15. Test 15; 75% Fill; θx = 0'; A_a = .09g; CRIT = 2.0%

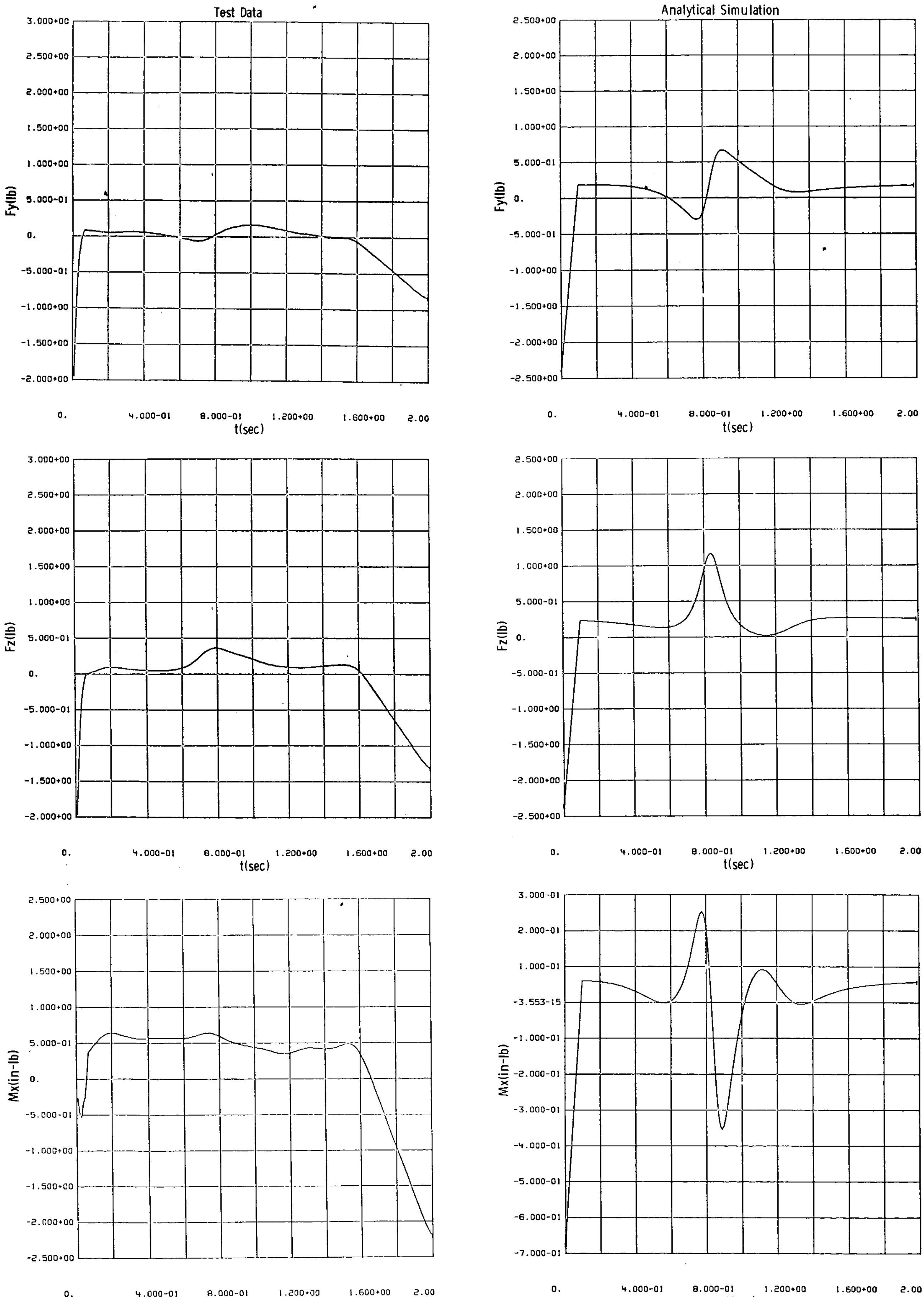


Figure C-16. Test 16; 25% Fill; $\theta x = 45^{\circ}$; $A_a = .09g$; CRIT = 2.0%

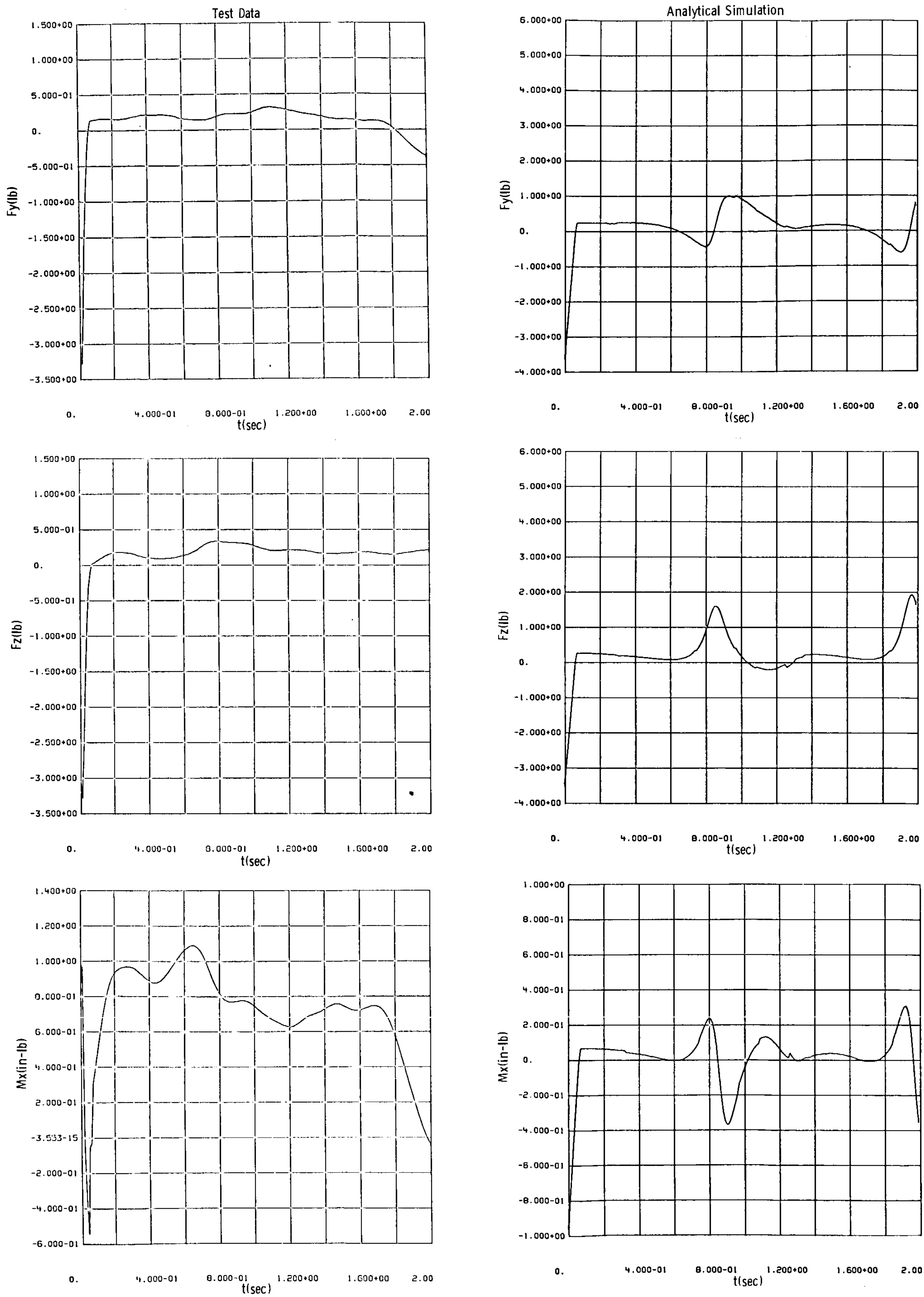


Figure C-17. Test 17; 50% Fill; $\theta x = 45^\circ$; $A_a = .09g$; CRIT = 0.5%

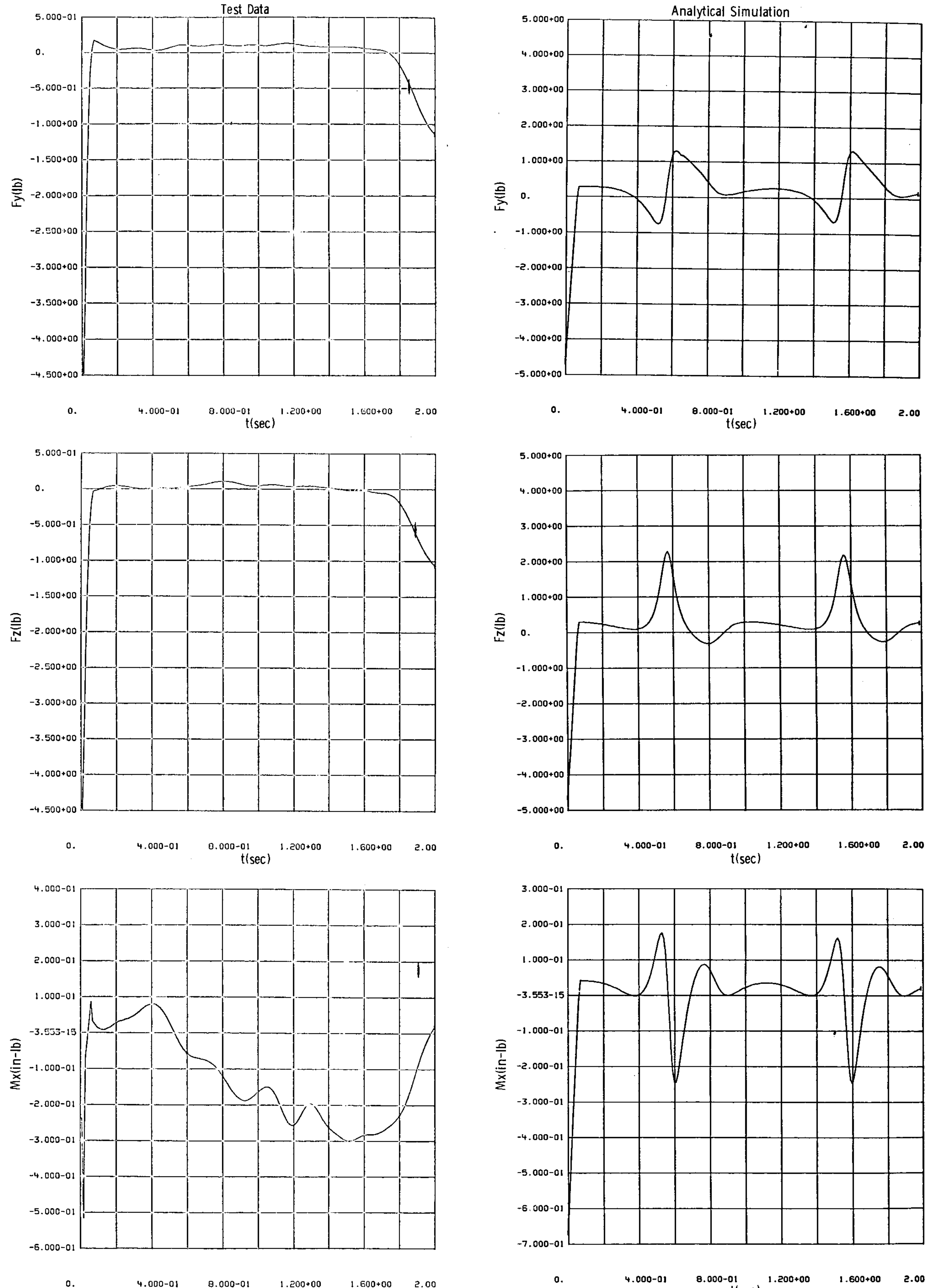


Figure C-18. Test 18; 75% Fill; $\theta x = 45^\circ$; $A_a = .09g$; CRIT = 2.0%

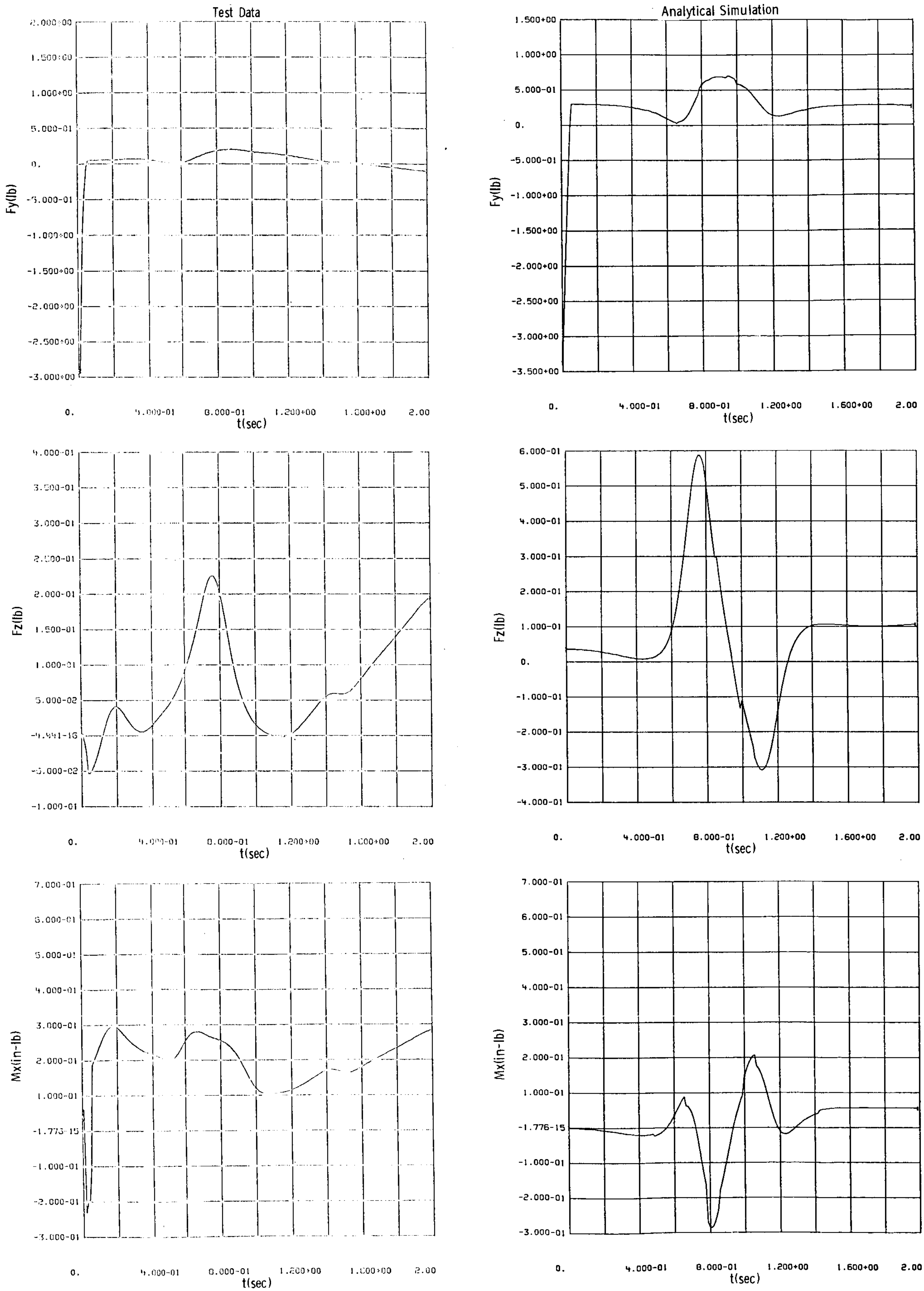


Figure C-19. Test 19; 25% Fill; $\theta x = 90^\circ$; $A_a = .09g$; CRIT = 0.5%

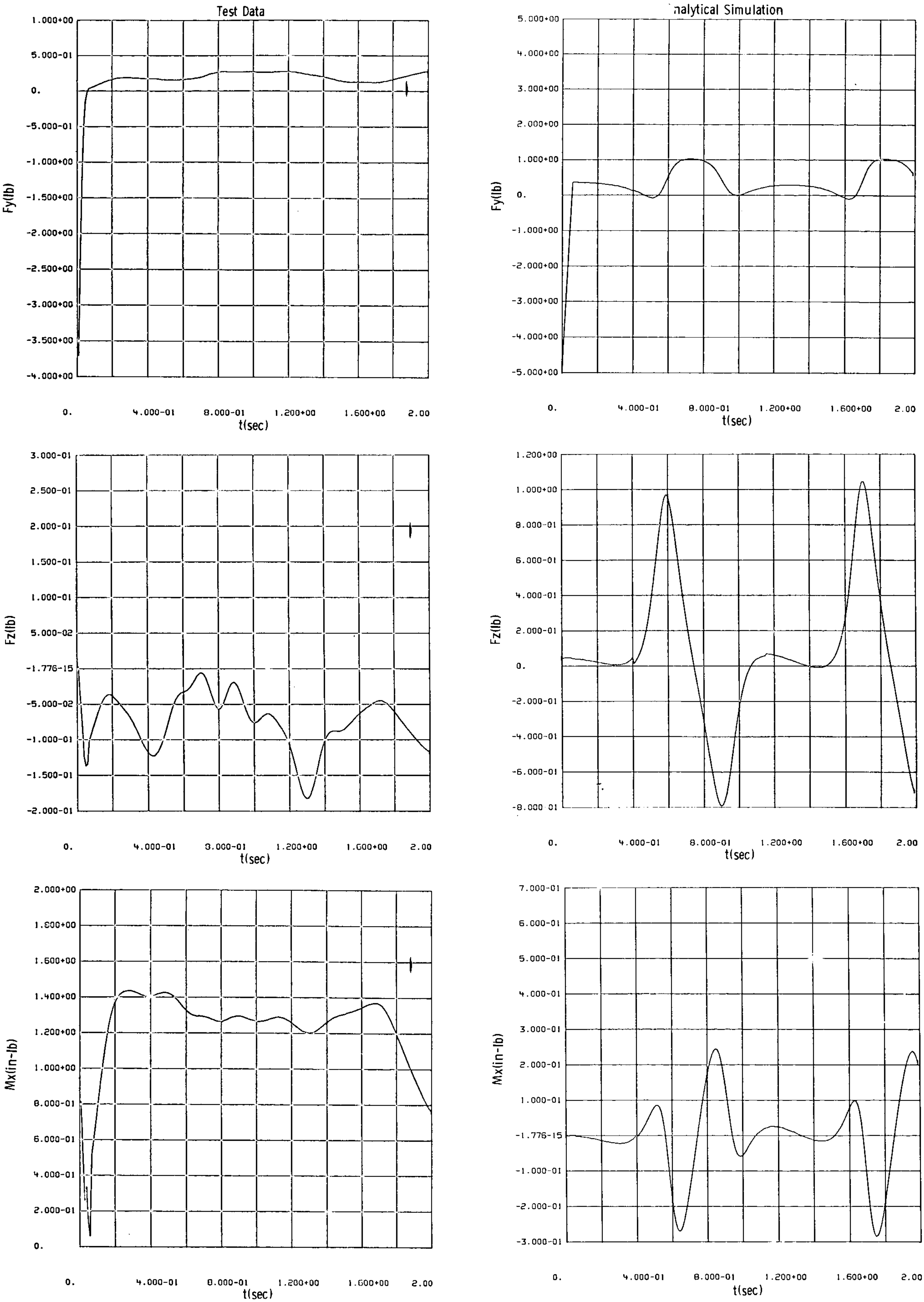


Figure C-20. Test 20; 50% Fill; $\theta x = 90^{\circ}$; $A_a = .09g$; CRIT = 2.0%

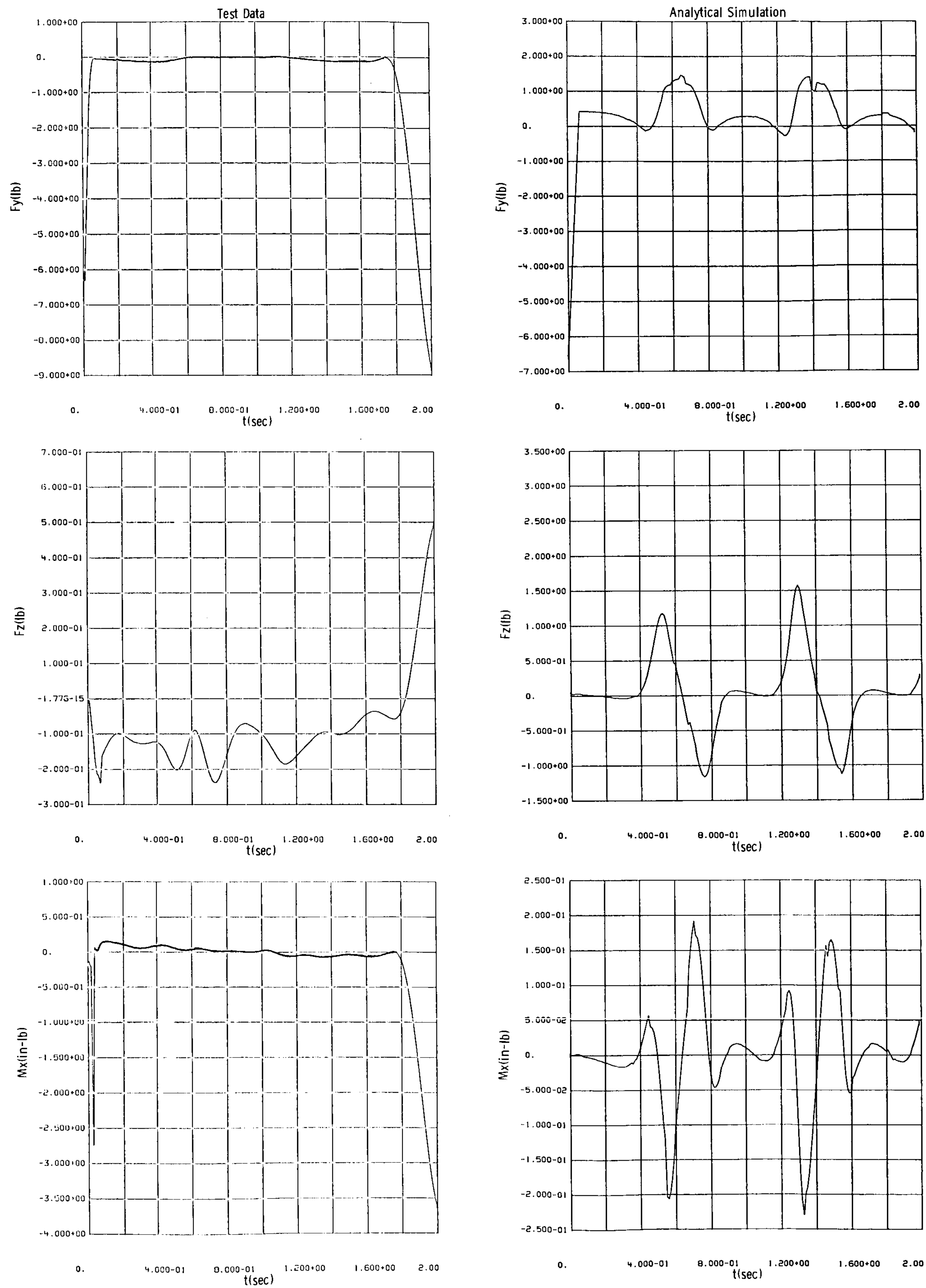


Figure C-21. Test 21; 75% Fill; $\theta x = 90^{\circ}$; $A_a = .09g$; CRIT = 0.5%

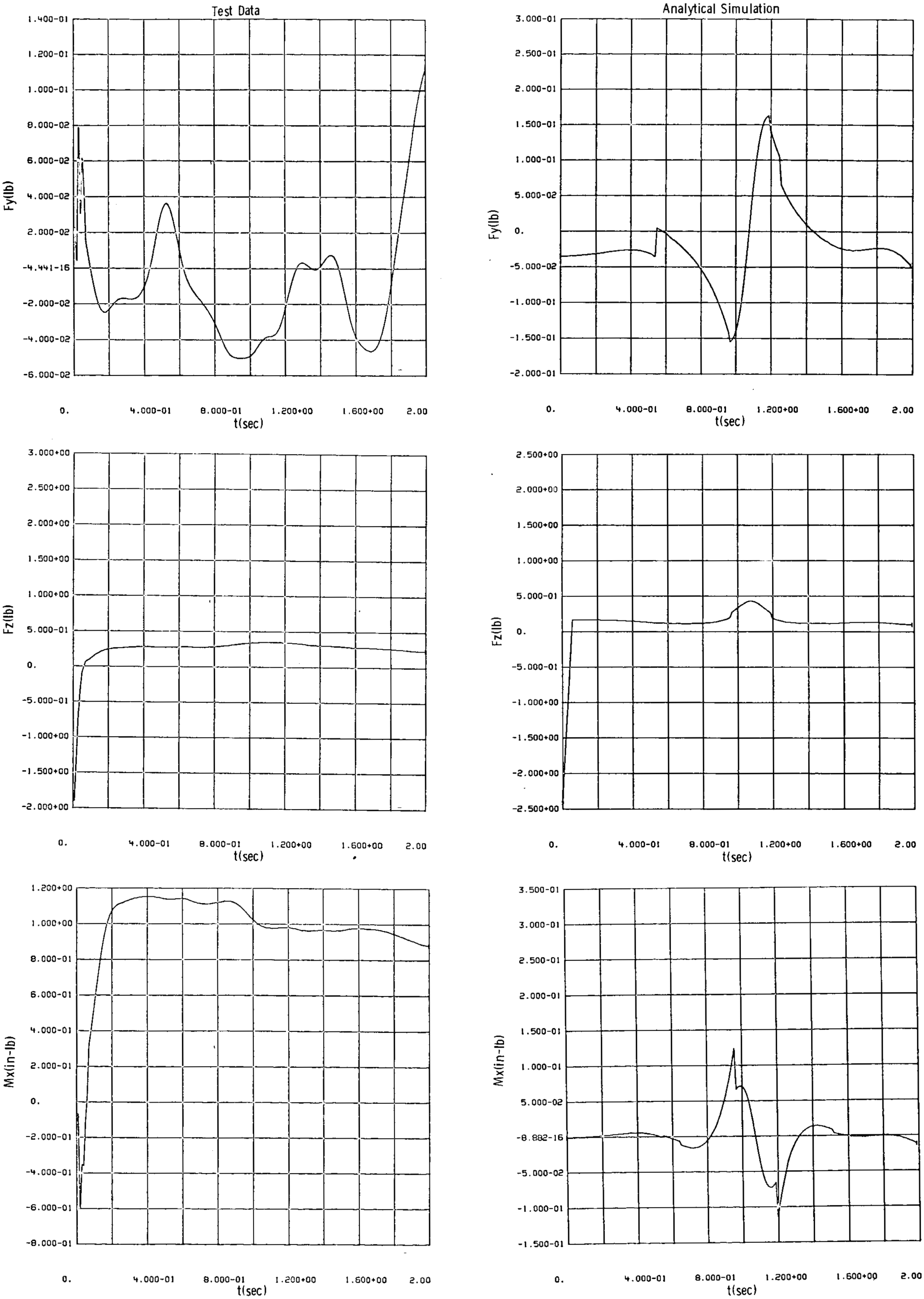


Figure C-22. Test 22; 10% Fill; $\theta x = 0^\circ$; $A_a = .09g$; CRIT = 2.0%

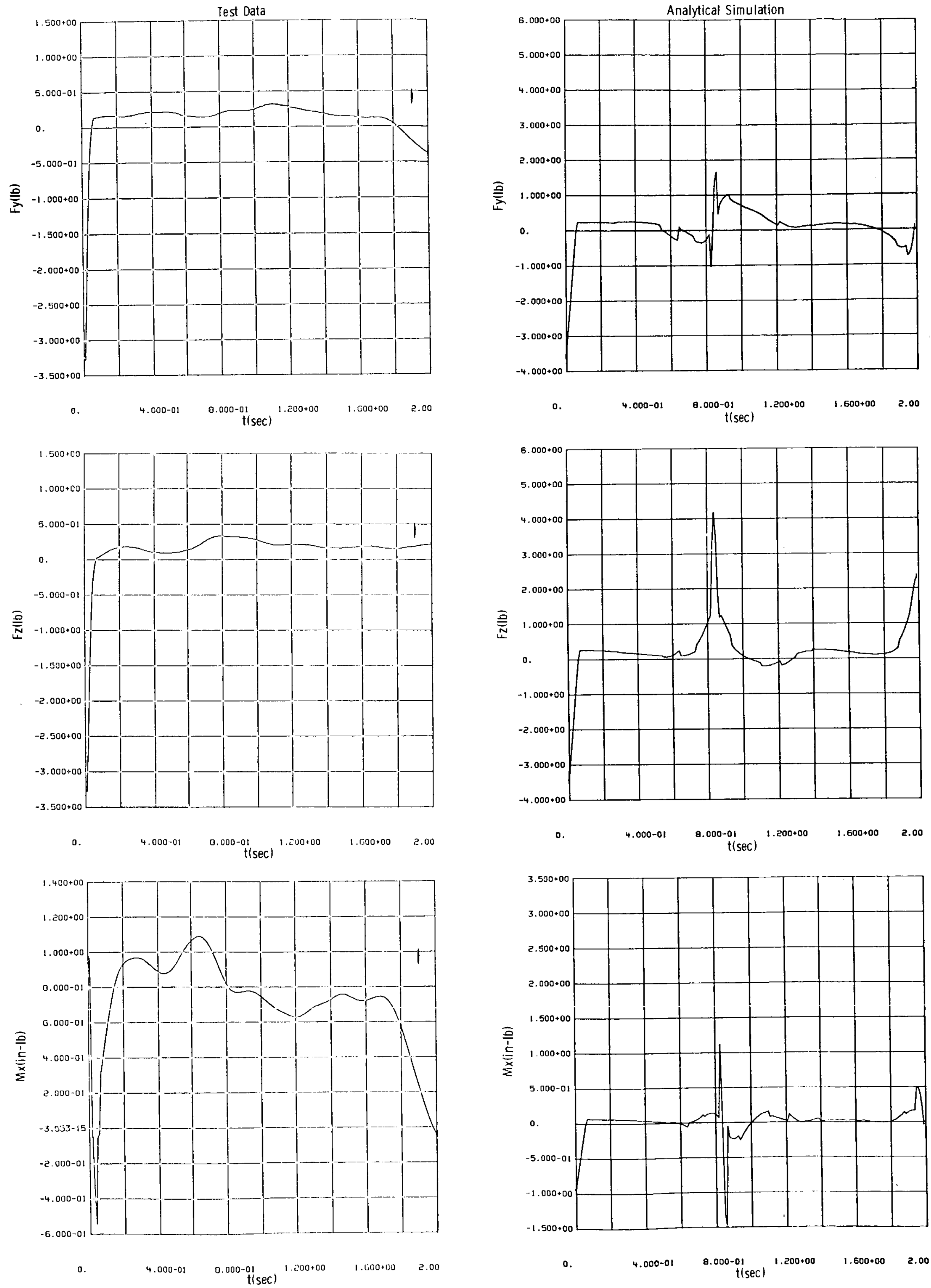


Figure C-23. Test 17; 50% Fill; $\theta x = 45^\circ$; $A_a = .09g$; CRIT = 2.0%

TABLE C-1. AXIAL AND LATERAL ACCELERATION TABLE

Test #	θX (deg)	% Fill	Time (sec)	AZI (in/sec^2)	AYI (in/sec^2)
1	0.0	25	0.0	386.04	4.0
			0.055	-16.49	4.0
			0.50	-16.49	4.0
			0.51	-16.49	11.66
			1.10	-16.49	11.66
			1.11	-16.49	2.00
			2.045	-16.49	2.00
2	0.0	50	0.0	386.04	4.75
			0.06	-16.79	4.75
			0.80	-16.79	4.75
			0.81	-16.79	-1.66
			1.05	-16.79	-1.66
			1.06	-16.79	3.80
			2.03	-16.79	3.80
3	0.0	75	0.0	386.04	2.81
			0.06	-16.79	2.81
			0.60	-16.79	2.81
			0.61	-16.79	1.00
			1.45	-16.79	1.00
			1.46	-16.79	3.12
			2.03	-16.79	3.12
4	30.	25	0.0	386.04	6.0
			0.07	-15.83	6.0
			2.08	-15.83	6.0

TABLE C-1 (cont.)

Test #	θX (deg)	% Fill	Time (sec)	AZI (in/sec^2)	AYI (in/sec^2)
5	30.	50.	0.0	386.04	2.45
			0.065	-16.40	2.45
			0.64	-16.40	2.45
			0.65	-16.40	0.0
			0.77	-16.40	0.0
			0.78	-16.40	3.9
			1.18	-16.40	3.9
			1.19	-16.40	0.0
			2.05	-16.40	0.0
6	30.	75.	0.0	386.04	2.60
			0.07	-15.92	2.60
			0.60	-15.92	2.60
			0.61	-15.92	3.60
			1.57	-15.92	3.60
			1.58	-15.92	7.50
			2.075	-15.92	7.50
7	60.	25.	0.0	386.04	5.62
			0.07	-16.69	5.62
			2.035	-16.69	5.62
8	60.	50.	0.0	386.04	3.50
			0.065	-16.59	3.50
			2.04	-16.59	3.50
9	60.	75.	0.0	386.04	2.5
			0.07	-15.92	2.5
			1.00	-15.92	2.5
			1.01	-15.92	0.62
			1.40	-15.92	0.62
			1.41	-15.92	3.33
			2.075	-15.92	3.33

TABLE C-1 (cont.)

Test #	θX (deg)	% Fill	Time (sec)	AZI (in/sec^2)	AYI (in/sec^2)
10	90.	25.	0.0	386.04	2.9
			0.06	-16.79	2.9
			0.58	-16.79	2.9
			0.59	-16.79	0.0
			2.03	-16.79	0.0
11	90.	50.	0.0	386.04	3.0
			0.06	-16.79	3.0
			0.60	-16.79	3.0
			0.61	-16.79	5.71
			0.83	-16.79	5.71
			0.84	-16.79	1.87
			2.03	-16.79	1.87
12	90.	75.	0.0	386.04	1.87
			0.065	-15.74	1.87
			0.64	-15.74	1.87
			0.65	-15.74	0.0
			0.88	-15.74	0.0
			0.89	-15.74	7.0
			1.05	-15.74	7.0
			1.06	-15.74	0.0
			1.57	-15.74	0.0
			1.58	-15.74	4.0
			2.085	-15.74	4.0
13	0.0	25.	0.0	386.04	8.33
			0.065	-34.43	8.33
			1.43	-34.43	8.33
			1.44	-34.43	0.62
			1.615	-34.43	0.62

TABLE C-1 (cont.)

Test #	θX (deg)	% Fill	Time (sec)	AZI (in/sec^2)	AYI (in/sec^2)
14	0.0	50.	0.0	386.04	6.66
			0.065	-34.18	6.66
			1.62	-34.18	6.66
15	0.0	75.	0.0	386.04	1.90
			0.06	-26.12	1.90
			0.25	-26.12	1.90
			0.26	-26.12	3.50
			0.70	-26.12	3.50
			0.71	-26.12	-4.00
			0.93	-26.12	-4.00
			0.94	-26.12	-3.00
			1.22	-26.12	-3.00
			1.23	-26.12	0.0
			1.81	-26.12	0.0
16	45.	25.	0.0	386.04	8.33
			0.10	-35.20	8.33
			1.60	-35.20	8.33
17	45.	50.	0.0	386.04	6.25
			0.065	-28.18	6.25
			0.29	-28.18	6.25
			0.30	-28.18	0.0
			1.30	-28.18	0.0
			1.31	-28.18	7.0
			1.755	-28.18	7.0
18	45.	75.	0.0	386.04	6.0
			0.065	-24.903	6.0
			0.65	-24.903	6.0
			0.66	-24.903	-1.0
			0.92	-24.903	-1.0

TABLE C-1 (cont.)

Test #	θX (deg)	% Fill	Time (sec)	AZI (in/sec^2)	AYI (in/sec^2)
			0.93	-24.903	2.5
			1.845	-24.90	2.5
19	90.	25.	0.0	386.04	8.0
			0.055	-34.69	8.0
			1.61	-34.69	8.0
20	90.	50.	0.0	386.04	10.0
			0.06	-28.58	10.0
			0.40	-28.58	10.0
			0.41	-28.58	3.2
			0.60	-28.58	3.2
			0.61	-28.58	2.14
			1.15	-28.58	2.14
			1.16	-28.58	4.16
			1.745	-28.58	4.16
21	90.	75.	0.0	386.04	5.83
			0.07	-25.59	5.83
			0.37	-25.59	5.83
			0.38	-25.59	3.33
			0.58	-25.59	3.33
			0.59	-25.59	-1.0
			0.85	-25.59	-1.0
			0.86	-25.59	4.16
			1.825	-25.59	4.16
22	0.0	10.	0.0	386.04	7.5
			0.06	-27.60	7.5
			0.54	-27.60	7.5
			0.55	-27.60	-0.50
			1.25	-27.60	-0.50
			1.26	-27.60	5.00
			1.77	-27.60	5.00

TABLE C-2. QUALITATIVE EVALUATION OF DROP TEST RESULTS

Test No.	Applied Accelerations	Fluid Motion	Measured Forces
1	Good	Good	Fair
2	Good	Good	Fair
3	Good	Ullage appeared as a bubble which traveled around tank wall	Fair
4	Good	Good	Good
5	Lateral slider stopped after .62 sec and movement was sporodic from .76 sec to end of test	Good	Fair
6	Good	Ullage appeared as a bubble which traveled around tank wall	Fair
7	Good	Good	Good
8	Good	Good	Fair
9	Good	Ullage appeared as a bubble which traveled around tank wall	Fair
10	Lateral slider stopped after .59 sec	Good	Fair
11	Good	Good	Good
12	Lateral slider stopped after .63 sec, and movement was sporodic from .86 sec to end of test	Ullage appeared as a bubble which traveled around tank wall	Fair
13	Good	Good	Excellent
14	Good	Good	Excellent
15	Lateral slider stopped after 1.2 sec	Ullage appeared as a bubble which traveled around tank wall	Fair

TABLE C-2 (cont.)

Test No.	Applied Accelerations	Fluid Motion	Measured Forces
16	Good	Good	Excellent
17	Good	Good	Good
18	Good	Ullage appeared as a bubble which traveled around tank wall	Fair
19	Good	Good	Excellent
20	Good	Good	Fair
21	Good	Ullage appeared as a bubble which traveled around tank wall	Fair
22	Good	Good	Good